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Pacific Northwest Laboratory Annual Report for 1984 to the DOE Office of Energy Research

Part 3 Atmospheric Sciences

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of Pacific Northwest Laboratory

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PREFACE

This 1984 annual report from Pacific Northwest Laboratory (PNL) to the Department of Energy (DOE) describes research in environment, health, and safety conducted during fiscal year 1984. The report again consists of five parts, each in a separate volume.

The five parts of the report are oriented to particular segments of our program. Parts 1 to 4 report on research performed for the DOE Office of Health and Environmental Research in the Office of Energy Research. Part 5 reports progress on all research performed for the Assistant Secretary for Policy, Safety, and Environment. In some instances, the volumes report on research funded by other DOE components or by other governmental entities under interagency agreements. Each part consists of project reports authored by scientists from several PNL research departments, reflecting the multidisciplinary nature of the research effort.

The parts of the 1984 Annual Report are:

Part 1: Biomedical Sciences Program Manager - J. F. Park	D. L. Felton, Report Coordinator and Editor
Part 2: Environmental Sciences Program Manager - B. E. Vaughan	B. E. Vaughan, Report Coordinator C. M. Novich, Editor
Part 3: Atmospheric Sciences Program Manager - C. E. Elderkin	N. S. Laulainen, Report Coordinator E. L. Owczarski, Editor
Part 4: Physical Sciences Program Manager - J. M. Nielsen	R. M. Garcia, Report Coordinator J. E. Danko, Editor
Part 5: Overview and Assessment Program Manager - W. A. Glass	R. W. Baalman, Report Coordinator and Editor

Activities of the scientists whose work is described in this annual report are broader in scope than the articles indicate. PNL staff have responded to numerous requests from DOE during the year for planning, for service on various task groups, and for special assistance.

Credit for this annual report goes to many scientists who performed the research and wrote the individual project reports, to the program managers who directed the research and coordinated the technical progresss reports, to the editors who edited the individual project reports and assembled the five parts, and to Ray Baalman, editor in chief, who directed the total effort.

W. J. Bair, Manager
S. Marks, Associate Manager
Environment, Health and Safety
Research Program

Previous reports in this series:

Annual Report for

1951	W-25021, HW-25709
1952	HW-27814, HW-28636
1953	HW-30437, HW-30464
1954	HW-30306, HW-33128, HW-35905, HW-35917
1955	HW-39558, HW-41315, HW-41500
1956	HW-47500
1957	HW-53500
1958	HW-59500
1959	HW-63824, HW-65500
1960	HW-69500, HW-70050
1961	HW-72500, HW-73337
1962	HW-76000, HW-77609
1963	HW-80500, HW-81746
1964	BNWL-122
1965	BNWL-280; BNWL-235, Vol, 1-4; BNWL-361
1966	BNWL-480, Vol. 1; BNWL-481, Vol. 2, Pt. 1-4
1967	BNWL-714, Vol. 1; BNWL-715, Vol. 2, Pt. 1-4
1968	BNWL-1050, Vol. 1, Pt. 1-2; BNWL-1051, Vol. 2, Pt. 1-3
1969	BNWL-1306, Vol. 1, Pt. 1-2; BNWL-1307, Vol. 2, Pt. 1-3
1970	BNWL-1550, Vol. 1, Pt. 1-2; BNWL-1551, Vol. 2, Pt. 1-2
1971	BNWL-1650, Vol. 1, Pt. 1-2; BNWL-1651, Vol. 2, Pt. 1-2
1972	BNWL-1750, Vol. 1, Pt. 1-2; BNWL-1751, Vol. 2, Pt. 1-2
1973	BNWL-1850, Pt. 1-4
1974	BNWL-1950, Pt. 1-4
1975	BNWL-2000, Pt. 1-4
1976	BNWL-2100, Pt. 1-5
1977	PNL-2500, Pt. 1-5
1978	PNL-2850, Pt. 1-5
1979	PNL-3300, Pt. 1-5
1980	PNL-3700, Pt. 1-5
1981	PNL-4100, Pt. 1-5
1982	PNL-4600, Pt. 1-5
1983	PNL-5000, Pt. 1-5

FOREWORD

The goals of atmospheric research at Pacific Northwest Laboratory (PNL) are to assess, describe, and predict the nature and fate of atmospheric contaminants and to study the impacts of contaminants on local, regional, and global climates. The contaminants being investigated are those resulting from the development and use of conventional resources (coal, gas, oil, and nuclear power) as well as alternative energy resources.

The description of atmospheric research at PNL is organized in terms of the following studies:

- Atmospheric Studies in Complex Terrain (ASCOT)
- Boundary Layer Meteorology
- Dispersion, Deposition and Resuspension of Atmospheric Contaminants.

Atmospheric Studies in Complex Terrain (ASCOT)

The ASCOT program represents a multilaboratory effort to coordinate research activities in the areas of boundary layer meteorology, transport and dispersion of contaminated air parcels, and the transformation, scavenging, and dry deposition of atmospheric contaminants in mountainous terrain settings. This coordination attempts to integrate theoretical analysis, model development, and the results of carefully designed field experiments. The improved understanding of transport and diffusion in complex terrain gained through this collaborative approach will allow the development of assessment models that can be applied with greatly improved reliability to the siting of energy-producing facilities in the western United States.

Boundary Layer Meteorology in Complex Terrain

Air pollution in mountainous regions is a particularly difficult problem because of the complexity of meteorological conditions over spatial scales ranging from individual valleys to systems of many valleys and ridges of a region, and the diurnal coupling/-decoupling phenomena between individual valleys and the regional convective boundary layer. In order to ensure acceptable siting of energy development facilities in uneven terrain, models and field measurements of complex airflow and dispersion conditions in this complex setting must be developed and undertaken.

Disperson, Deposition and Resuspension of Atmospheric Contaminants

Dispersion, deposition, and resuspension process are linked intimately with the dynamics of the boundary layer. The former two processes act to reduce air concentrations of gaseous and particulate material while the latter process acts to increase air concentrations of particulate material, particularly in the large particle size classes. In many energy development areas of the West, all three processes will play an important role in determining the effective residence times of potentially hazardous particles in the atmosphere. The current program is aimed at gathering necessary field data and developing models for the prediction of the dispersion, deposition and resuspension of atmospheric contaminants.

This report describes the progress in FY 1984 for each of these areas. A divider page summarizes the goals of each area and lists, as bulleted items, project titles that support research in each area.

CONTENTS

Atmospheric Studies in Complex Terrain– 1984 Activities

ATMOSPHERIC STUDIES IN COMPLEX TERRAIN — 1984 ACTIVITIES

- **Atmospheric Boundary Layer Studies**
- **Atmospheric Diffusion in Complex Terrain**
- **Coupling/Decoupling of Synoptic and Valley Circulations**

A major focus of research activities at PNL is related to the multilaboratory Atmospheric Studies in Complex Terrain (ASCOT) program. Initial experience was gained at the Geysers geothermal site in northern California during 1979, 1980, and 1981. In 1982 the area of study shifted from the Geysers area to the oil-shale region in western Colorado, where a series of scoping experiments was performed. Evaluation of those experiments, as well as the experience gained at the Geysers, led to the design of experiments conducted in Colorado in 1984.

During the period of September 17 through October 6, 1984, the ASCOT program supported an extensive field study in the Brush Creek valley of western Colorado. The major goals of this study were to measure the mass, momentum, and thermal energy budgets of Brush Creek valley and to measure the transport and diffusion of tracers during nocturnal drainage flow and during the morning breakup of drainage flow.

This extensive measurement program was a cooperative effort by universities and several Department of Energy (DOE) and National Oceanic and Atmospheric Administration (NOAA) laboratories:

Pacific Northwest Laboratory (PNL)
Argonne National Laboratory (ANL)
Atmospheric Turbulence and Diffusion Laboratory (ATDL)
Lawrence Livermore National Laboratory (LLNL)
Los Alamos National Laboratory (LANL)
Wave Propagation Laboratory (WPL)
Colorado State University (CSU)
University of Washington (UW)

This section of the report begins with an article that gives a summary of PNL participation in the ASCOT 84 experiments. This article is followed by detailed descriptions of measurements and results obtained during the experiments.

The improved understanding of transport and diffusion in complex terrain gained through the ASCOT study will allow the development of environmental assessment models that can be applied with greatly improved reliability to the siting of energy-producing facilities in the western United States.

THE ASCOT PROGRAM—PACIFIC NORTHWEST LABORATORY'S CONTRIBUTION OF THE DEPARTMENT OF ENERGY'S MULTI-LABORATORY COMPLEX TERRAIN FIELD PROGRAM, JUNE AND SEPTEMBER - OCTOBER 1984

M. M. Orgill, T. W. Horst, J. C. Doran, C. D. Whiteman, K. J. Allwine, J. M. Thorp, R. I. Schreck, C. G. Lindsey, G. F. Athey, D. W. Glover, R. N. Lee, O. B. Abbey, J. G. Droppo, C. S. Glantz, and J. M. Hubbe

This article presents an overview of the contributions by the Pacific Northwest Laboratory (PNL) to the ASCOT field program conducted in Brush Creek valley of western Colorado between September 17 and October 6, 1984. Five multiple perfluorocarbon tracer experiments were conducted to provide data on atmospheric transport and diffusion during nighttime and the morning daylight hours. The meteorological data base that results from the experiments will be useful in developing computer models of contaminant transport and dispersion in complex terrain, such as might be applied in the siting of energy-producing facilities in the western United States.

The main objectives of PNL's ASCOT 84 field program were to evaluate

- mass, momentum, and energy fluxes of valley and slope flows
- transfer of mass, momentum, and energy between the valley and the free-air stream above the valley
- turbulence over the valley and sidewalls
- the surface energy budget of the valley
- the wind and temperature over the region surrounding the Brush Creek valley.

PNL's field effort during ASCOT 84 consisted of the following tasks:

- collecting wind, temperature, humidity and pressure profiles from three sites (Rifle, Meeker and Rangley) using RD-65A rawinsondes. On experimental nights upper-level soundings were started at 1700 MDT and continued every 3 hours until 1400 MDT of the next day. The National Weather Service at Grand Junction also completed upper-air soundings on the same schedule during experimental periods.
- collecting data on the energy and radiation budget of the valley by operating five energy balance (Bowen ratio) stations. Two stations were located in the valley. There was one on each sidewall and a fifth station was located on Skinner Ridge (see the article by Orgill and Whiteman, "Surface Energy Budget Components Over a Complex Terrain Area," in this annual report).
- collecting temperature, humidity, pressure, and wind data up to about 700 m with two tethered balloon systems, one located on the valley floor 3 km upvalley from the entrance (PNL site) and the other on the west sidewall at about 145 m above the PNL valley site (see the article by Horst and Doran, "ASCOT Field Studies in Western Colorado," in this annual report).
- assisting with the establishment and layout of the multiple perfluorocarbon tracer sampling network that covered Brush Creek, Carr Creek, Clear Creek, Roan Creek, Brush Mountain, and Skinner Ridge (see the article by Allwine, Lee, and Orgill, "Real-Time Measurements of Multiple Perfluorocarbon Tracers During the 1984 ASCOT Experiments," in this annual report).
- providing photographic documentation of smoke tracers released from a side canyon of Brush Creek (Pack Canyon) approximately 5.5 km upvalley from the entrance of Brush Creek (see the article by Thorp and Orgill, "Nocturnal Photography of Smoke Tracers in Complex Terrain," in this annual report).
- providing real-time tracer concentration data at the site in the valley by operating a dual-trap perfluorocarbon gas chromatograph. Data were collected for the

last two experimental periods (see the article by Allwine, Lee, and Orgill, "Real-Time Measurements of Multiple Perfluorocarbon Tracers During the 1984 ASCOT Experiments," in this annual report).

- collecting path-averaged along-valley wind components by operating two laser anemometers at 34 m and 66 m above the PNL valley site (see the article by Horst and Doran, "ASCOT Field Studies in Western Colorado," in this annual report).

- collecting wind, turbulence, and temperature data at two tower sites. A 15-m tower at the PNL valley site was instrumented with two sonic anemometers and fast-responding temperature sensors. In addition, Gill® anemometers collected wind data at 5 levels and temperature sensors collected temperature data at 6 levels. A 9-m tower was located on the western sidewall near the tethersonde site and was instrumented at 5 levels for wind and temperature measurements (see the article by Horst and Doran, "ASCOT Field Studies in Western Colorado," in this annual report).

- collecting data on temperature inversions (intensity of backscatter) and the three components of the wind at the PNL valley site by operating a Doppler sodar during the experimental periods. Data were obtained up to 500 m on most experimental periods (see the article by Horst and Doran, "ASCOT Field Studies in Western Colorado," in this annual report).

- collecting radiance or surface radiation temperature data from different soil and vegetation types in the valley by operating a precision radiation thermometer at the PNL valley site. Data were collected on an intermittent basis because of manpower and weather restrictions (see the article by Orgill and Whiteman, "Surface Energy Budget Components Over a Complex Terrain Area," in this annual report.)

- providing mobile radios and radio repeaters for field communication. One repeater was located on Kimball Mountain just south of Brush Creek and a second one was located on Mount Callahan (Roan Cliffs) above the town of Parachute.

The topography of Brush Creek valley and the locations of field operations are illustrated in Figure 1. Brush Creek is a tributary of Roan Creek. Roan Creek joins the Colorado River from the north at the town of De Beque, which is located about 53 km upriver (east) from Grand Junction, Colorado. Brush Creek valley trends in a general northwest direction for about 25 km from its junction with Roan Creek. For the lower 10 to 15 km of its course, Brush Creek flows through a narrow, steep-walled canyon about 0.6 km wide and about 600 m deep. Several short, precipitous, intermittent streams have, in places,

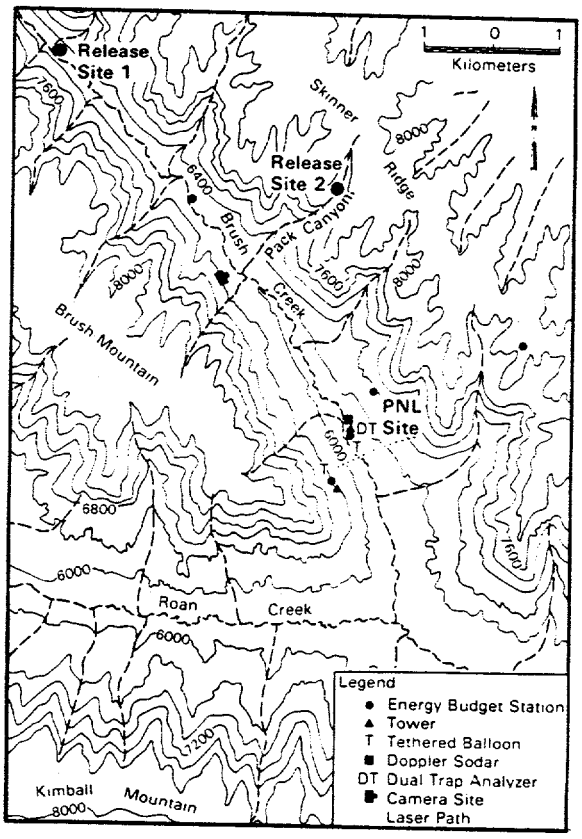

FIGURE 1. Location of PNL Field Activities During ASCOT Field Program in Brush Creek, Colorado. Isopleths are in feet.

®The Gill anemometer is manufactured by the Ralph M. Young Co., of Traverse City, Michigan.

cut well back into the sidewalls of the canyon, especially on the east side.

The five perfluorocarbon tracer experiments were conducted during the nighttime and early daylight hours, i.e., between 2300 MDT and 1200 MDT. Three of the experiments were conducted under light synoptic wind conditions and two experiments were accomplished with some interference from inclement weather. Two experiments were cancelled because of strong winds or thunderstorms. Table 1 lists the dates of the experimental periods for the September-October field program.

The Brush Creek field program was a multi-laboratory effort, and PNL's activities were performed in cooperation with these other laboratories. For example, two tethered-balloon sites operated by PNL were part of a network of fourteen tethered balloons. The two laser anemometer sites were part of a network of seven optical anemometer paths. Additional instrumented towers, Doppler sodars and a Doppler lidar supplemented the field effort.

Preliminary evaluation of part of PNL's Brush Creek data base is presented in the following articles in this annual report. Data will be processed, edited and put on magnetic tapes to be sent to the ASCOT data bank at Lawrence Livermore National Laboratory.

TABLE 1. ASCOT Experiments Conducted During September and October 1984 at Brush Creek Valley

Experiment	Date	Remarks
0	Sept. 17-18	Smoke release but no tracer; meteorological measurements
1	Sept. 19-20	Meteorological measurements; tracer and smoke release
2	Sept. 23-24	Experiment cancelled; strong southerly winds; frontal passage ~1545 MDT
3	Sept. 25-26	Meteorological measurements; tracer experiment; smoke experiments cancelled after 0300 MDT; faulty searchlight
4	Sept. 27-28	Meteorological measurements; tracer and smoke release; equipment problems; frontal passage during the night
5	Sept. 29-30	Meteorological measurements; tracer and smoke release
6	Sept. 30-Oct. 1	Experiment cancelled; rain and thunderstorms
7	Oct. 5-6	Meteorological measurements; tracer experiment; cloudy and rain until midnight; smoke tracer release delayed until 0400 MDT

• Atmospheric Boundary Layer Studies

The objectives of these studies are:

To investigate the meteorological characteristics of the planetary boundary layer that pertain to contaminant transport and dry removal.

To analyze the transport and diffusion of contaminants in complex terrain, particularly for the western slope of the Rocky Mountains in Colorado and The Geysers Geothermal Area of California.

To construct simple models for the prediction of the depth, speed, and direction of gravity-controlled drainage flows and of turbulence and contaminant dispersion within these flows.

To examine nocturnal valley flow by developing a simple model for the mass, momentum, and thermal energy budgets in a valley and by taking measurements of valley flow structure.

ASCOT FIELD STUDIES IN WESTERN COLORADO

T. W. Horst and J. C. Doran

The PNL contributions to the Brush Creek mass, momentum, and thermal energy budget measurements were mostly located in an area from 1.5 to 2 mi above the mouth of Brush Creek. They can be divided into three groups whose purposes were principally to measure 1) the surface fluxes of momentum, heat and moisture, 2) the advection of mass, momentum and heat within the valley flow, and 3) the advection of mass, momentum, and heat within the slope flows.

The near-surface vertical fluxes of momentum and heat were measured directly with two sonic anemometers and two platinum resistance thermometers, which were mounted at heights of 3 and 10 m on a 15-m tower located on the floor of the valley. These fast-response instruments were supplemented with 3-component propeller anemometers at heights of 2, 3, 6, 10 and 16 m and aspirated thermistors at heights of 0.5, 2, 3, 6, 10 and 15 m. The slower response instruments provide profiles of wind and temperature to evaluate the applicability of flux-gradient relationships measured over flat terrain to a complex terrain site and provide supplementary estimates of the momentum and heat fluxes. Data from the tower were recorded continuously on 9-track magnetic tape at a rate of either 2.8 or 14 Hz for the fast-response instruments and at a rate of either 0.2 or 1 Hz for the slower response instruments The faster recording rates were used on the intensive measurement nights during which tracer releases were made.

Vertical fluxes of heat and moisture were also estimated at this site by measuring a surface energy budget. The surface radiation balance and the soil heat flux were measured directly and the net energy input to the atmosphere was partitioned between the sensible and latent heat fluxes using the Bowen ratio technique. Similar energy budgets were measured at four other sites that included a second site on the valley floor, a site on each sidewall, and a site on the plateau above the valley. Details of this measurement program are given in the article by Orgill and Whiteman, "Surface Energy Budget Components Over a Complex Terrain Area," in this volume.

The advection of mass, momentum and energy within the valley flow was estimated by measuring vertical profiles of wind and temperature at several locations in Brush Creek Valley. Several techniques were used at the valley cross-section instrumented by PNL, including the 15-m micrometeorological tower, a Doppler sodar, path-averaging laser anemometers, and soundings with tethered balloon systems. The Doppler sodar measured the three components of the wind from a height of 45 m to heights ranging from 300 to 500 m, depending on the thermal structure of the atmosphere. The 15-m tower and Doppler sodar wind measurements in the center of the valley were supplemented with two path-averaging

laser anemometers that measured the along-valley wind on cross-valley paths between the two sidewalls. These two paths were located at heights of 34 and 66 m above the tower/sodar site.

On the intensive measurement nights, wind and temperature profiles in the valley were also measured with two tethered balloon systems. These profiles were made from the surface to heights of 700 to 800 m at 90-min intervals beginning at 2330 and ending at 1000 MST. One balloon was flown from the tower/sodar site, and the second balloon was flown from a site on the west sidewall of Brush Creek 145 m above the tower/sodar site. The profiles measured from the western sidewall site will be used to investigate the cross-valley variation of the wind and temperature structure.

The occurrence and structure of slope flows were investigated by measuring wind and temperature profiles from a 10-m tower located at the western sidewall site described above. The purpose of these measurements was to estimate the advection of mass, momentum and heat within the slope flows. These tower measurements were made only on the intensive measurement nights.

In order to complete the Brush Creek meteorological budgets, similar sets of measurements have been made by other participants in the ASCOT field study. All participants have agreed to reduce and exchange their meteorological data by April 1, 1985. Plans are currently being made at PNL to coordinate with other participants in analyzing this data and evaluating the meteorological budgets.

• Atmospheric Diffusion in Complex Terrain

Objectives of this study are:

To assist a multi-laboratory program studying diffusion in complex terrain by providing methodologies and techniques for analyses of transport and diffusion over a variety of complex landforms.

To evaluate and develop various transport and dispersion models for complex terrain.

PHOTOGRAPHY OF SMOKE TRACERS IN A VALLEY

M. M. Orgill and J. M. Thorp

As one task of the ASCOT field program of 1984, a PNL photographic team was assigned to obtain nighttime sequential photographs of smoke tracer plumes in Brush Creek valley. A week-long series of preliminary site- and equipment-testing investigations was conducted in June 1984. The major photographic and meteorological experiments were conducted during a 4-week period in September and early October.

The lower 10 km of Brush Creek valley and one of the east wall tributary gulches, labelled Pack Canyon, were chosen for both series of experiments (Figure 1 on p. 8). The experiments were designed to provide photographic information on the nocturnal drainage flow pattern in Brush Creek valley and the contribution, if any, to that flow from drainage coming from a typical side canyon such as Pack Canyon.

Meteorological measurements of the Brush Creek nocturnal drainage flow features are described elsewhere in this report. Some meteorological measurements were also made of wind, temperature, and moisture profiles at locations in Pack Canyon by LLNL and ANL. However, to study details of the interaction of drainage flow from Pack Canyon with that from Brush Creek, time series photographic observations were made of smoke that was introduced into upper Pack Canyon from a generation site (release site 2) in the gully above the steepest part of the canyon (see Figure 1 on p. 2).

The Pack Canyon drainage begins as a vegetated gully sloping southwestward from the 2500 m MSL crest of Skinner Ridge (see Figure 1 on p. 8). At about 2315 m MSL, this gully terminates at a 60-m-high vertical cliff that features a waterfall during wet weather. Release site 2 was located a short distance up the gully from this cliff. Below the cliff, the Pack Canyon drainage drops via a steep, curving course to about 1950 m MSL. One of the ANL tethersonde sites was located near this juncture with another steep fork of Pack Canyon. Below the merger of the two sub-drainages the gradient of Pack Canyon eases for the remaining distance to its confluence with Brush Creek at about 1825 m MSL.

During the five tracer, and one non-tracer, release experiments of the autumn series, 10- to 15-min ground-level smoke releases were generated hourly at release site 2 during the nighttime hours of the experimental periods. The PNL camera site for photographing the behavior of the smoke in Pack Canyon and Brush Creek was located on the western wall of Brush Mountain, opposite the mouth of Pack Canyon. The camera site was at about 1865 m MSL (see Figure 1 on p. 2). Two cameras were used, one pointed directly toward Pack Canyon, and the other pointed down Brush Creek valley. However, the fields of view overlapped so that both included the south wall of Pack Canyon. Thus, photographs taken simultaneously on both cameras provided a panoramic view of both Pack Canyon and lower Brush Creek.

Except during a few hours of low-intensity moonlight during the late-night portions of the first two experiments (September 18 and 20), the smoke puffs were illuminated by a large arc light of the type used for aircraft spotting during World War II. This type of light produces a narrow, but intense, beam of light. The searchlight was mounted on a yoke arrangement, which permits the operator to aim the beam in any direction above the horizontal plane. The photographic procedure was to expose color negative film for periods of

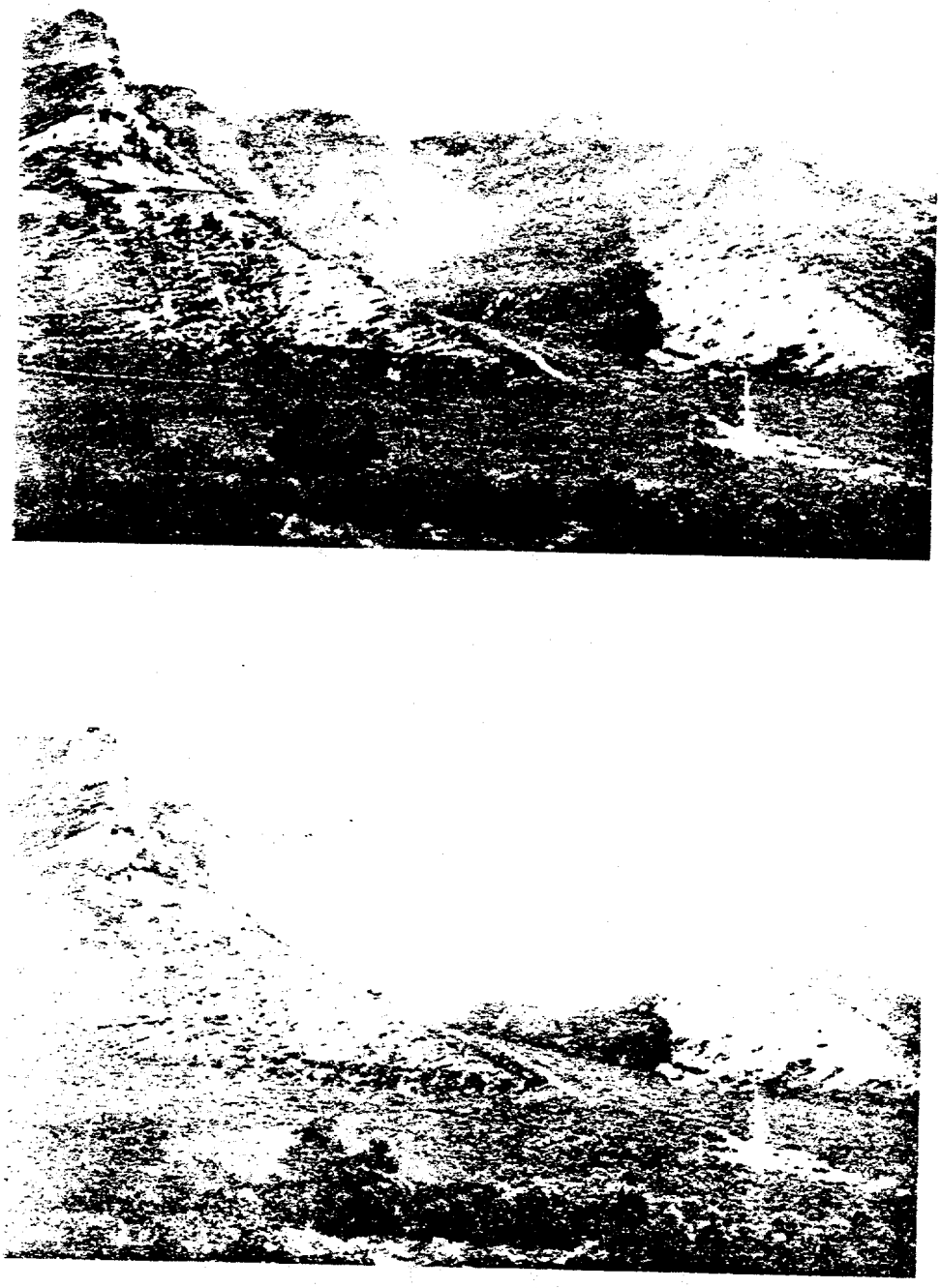

FIGURE 1. Smoke Plume in Pack Canyon from the Fourth Release of Experiment 0 at 0300 MST (top) and 0311 MST (bottom). The top photograph shows the "waterfall" type of smoke behavior observed during the first few minutes of most of the nighttime smoke releases. The bottom photograph shows the smoke plume diffusing at about the 2000 m MSL level in Pack Canyon. The diffused portion of the plume is starting to drift south (right) toward and over the south wall of Pack Canyon into Brush Creek. This pattern of transport occurred for most of the smoke releases.

5 to 240 s, during which times the searchlight operator "painted" the smoke puff with a series of horizontal passes of the light beam. When the puffs first appeared at the vertical cliff high in Pack Canyon, their areal extent was small, and thus little or no movement of the light beam was required and a short photographic exposure was possible. As the smoke puff increased in size by diffusion, longer exposures were required to allow the searchlight operator sufficient time to cover the extent of the smoke with light.

Two high-speed films were used: Kodacolor®, ISO 1000 and Fujicolor®, ISO 1600. A series of bracketing time exposures was made during the first experiment, and the film was processed that same day to permit determination of exposures that produced the best results.

®Trademarks of the Eastman Kodak Co., Rochester, New York, and the Fuji Photo Film Co., Ltd., Tokyo, respectively.

When photographic films are exposed for much longer times than those for which they are designed, their response to light becomes nonlinear. No estimate of this reciprocity factor was determined for the exposure times used during these experiments.

Table 1 contains a brief description of each of the eight experiments. Experiments 2 and 6 each were cancelled after a short time because of adverse meteorological conditions. No smoke was generated during experiment 2 (September 23-24). During experiment 6, on October 1, two smoke releases were made, but in each instance upvalley flow carried the smoke up the gully from the generation site. This area was invisible from the camera site. No photographs were made during either of these experiments.

One of the basic goals considered in the design of the 1984 ASCOT experiments was to

TABLE 1. Experiment Dates and Conditions During Autumn 1984 Brush Creek Experiments

Exp. No.	Date	Tracer Release	Pack Canyon Smoke Releases	Comments
0	Sept. 18	No	5	Some searchlight problems. Last smoke releases photographed by moonlight. Smoke behavior similar from release to release.
1	Sept. 20	Yes	7	Smoke behavior similar. Poured like water over the vertical cliff, diffused to near ANL site then flowed up and over the south wall of Pack Canyon.
2	Sept. 23-24	No	None	Experiment cancelled after 3 hours due to strong winds.
3	Sept. 26	Yes	3	Searchlight problems after 3 smoke releases.
4	Sept. 28	Yes	4	Smoke generator problems until 0230 MST. Searchlight failure after 0330 MST.
5	Sept. 30	Yes	7	Smoke behaved somewhat differently from release to release.
6	Oct. 1	No	2	Smoke was carried up the gully from the generator by up-valley winds. Experiment cancelled at 0145 MST because of thundershowers and overcast sky.
7	Oct. 6	Yes	3	No smoke releases until 0400 MST because of muddy roads to generation site. Variability in smoke behavior from release to release.

learn more about the source of the air that makes up the drainage flow down steep-sided valleys.

In a general way the behavior of smoke puffs in the Pack Canyon-Brush Creek drainage was similar throughout the six completed experiments. Photographs of the smoke releases for experiments 0 and 1 show that there was considerable similarity in the Pack Canyon drainage on those nights. As seen from the camera site, the smoke first appeared as a narrow stream, cascading over the vertical cliff much like water. Diffusion of the plumes was noticeable below 2150 m MSL. Little or no smoke descended below 2000 m MSL, and the smoke cloud exited Pack Canyon over the south wall and moved down Brush Creek high along its east wall (Figure 1).

A split plume at the waterfall cliff occurred on the third smoke release of experiment 3. Most of the smoke cascaded down the cliff, but a portion of the plume was carried north along the visible skyline. Diffusion of the plume appeared to be more rapid than in experiments 0 and 1. Searchlight failure caused cancellation of the photography exercise after three releases.

The behavior of smoke from releases made during experiments 4, 5, and 6 varied somewhat not only between experiments, but also between releases during the same experiments. However, smoke was rarely, if ever, observed below 2000 m MSL during any of the experiments. Some prominent layering of the smoke cloud within Pack Canyon was noted in experiment 5. The smoke released during all of the experiments eventually exited Pack Canyon by crossing over the south wall above about 1975 m MSL. Usually the thinning smoke cloud was then observed to move down the eastern side of Brush Creek valley. A double plume down Brush Creek was observed both visually, and by the WPL lidar, during experiment 7. Near sunrise, smoke from the last release of this experiment was also observed from the camera site to be well out over Brush Creek.

Qualitative analysis of the time series photographs of smoke behavior in Pack Canyon and lower Brush Creek will be performed in greater detail as the related meteorological data become available.

REAL-TIME MEASUREMENT OF MULTIPLE PERFLUOROCARBON TRACERS DURING THE 1984 ASCOT EXPERIMENTS

K. J. Allwine, R. N. Lee, and M. M. Orgill

This article describes the measurement of the perfluorocarbon tracers released during the 1984 ASCOT field experiments in Brush Creek valley. During each experiment, three tracers were released at two locations (release sites 1 and 2) shown in Figure 1, p. 2. The three perfluorocarbons released were C_6F_{12} (perfluoromethylcyclopentane - PMCP), C_7F_{14} (perfluoromethylcyclohexane - PMCH), and C_8F_{16} (perfluorodimethylcyclohexane - PDCH). The tracer PDCH was released at 220 m above the valley floor from site 1, and PMCH was released from the same site at ground level. PMCP was released at the head of a box canyon in the eastern sidewall of Brush Creek valley. The releases ran continuously from typically 0000 MST to 0800 MST.

A network of 93 ground-level sample collection units was set up over the study region to collect typically half-hour and one-hour integrated samples. The samples were collected in tubes containing a sorbent and were sent to laboratories for subsequent analysis. The samples were collected typically through the period from 0000 to 1200 MST. Ground-level samplers were located on Skinner Ridge, on Brush Mountain, in Brush Creek valley, in Carr Creek (western side of Brush Mountain), in Clear Creek (eastern side of Skinner Ridge), and in Roan Creek as far downvalley as De Beque (about 35 km from release site 1). In addition to the ground-level samplers, vertical samplers were also deployed on balloons up to 700 m above the valley floor. Vertical sampling was performed at 10 locations and the resulting sampling tubes were sent to laboratories for subsequent analysis.

To supplement the ground-level sampling plus provide the only in-the-field measurements of the tracers, PNL operated its dual-trap perfluorocarbon gas chromatograph. Real-time measurements of the three perfluorocarbon tracers were made simultaneously at the PNL motor home site, which was on the floor of the Brush Creek valley about 3 km upvalley

from Roan Valley as shown in Figure 1, p. 2. The location was about 8 km downvalley from release site 1 and about 5 km downvalley from release site 2.

Dual-Trap Perfluorocarbon Analyzer

The dual-trap analyzer consists of a pair of adsorption traps interfaced with a gas chromatograph equipped with an electron capture detector. During operation, perfluorocarbons in ambient air are collected on one trap while the other trap is analyzed, then the traps switch roles and the collection-analysis cycle proceeds. A vacuum pump is used to push a metered flow of ambient air through the trip, which consists of a stainless steel tube (6 in. long by 1/8 in. OD) packed with a sorbent. At the end of the sampling interval a Digital Valve Sequence Programmer[a] switches the 8-port sampling valve and brings the second adsorption trap into the air sample stream while the loaded trap is backflushed to remove oxygen. Next, a valve is switched connecting the loaded trap to the carrier stream of the gas chromatograph and rapid ohmic heating of this trap releases adsorbed components of ambient air to the chromatograph for separation on the column and detection via the electron capture detector. Components in ambient air that may interfere with perfluorocarbon detection are destroyed and removed by an in-line catalytic reactor and diffusion drying tube.

The operating conditions of the dual-trap analyzer during the 1984 ASCOT experiments are given in Table 1. Five-minute integrated measures of the three perfluorocarbon tracers were made continuously through the experimental periods.

Results and Discussion

Real-time measurements of the three perfluorocarbon tracers were made during the last two ASCOT tracer experiments: the September 30 experiment and the October 6 experiment.

Figure 1 shows a chromatogram from one 5-min analysis cycle. During this cycle, Trap 1 was backflushed for 0.2 min to drive off the ambient oxygen, desorbed for 0.4 min to release the adsorbed materials to the carrier gas stream, and then backflushed for the remaining 4.4 min. Trap 2 was collecting an ambient air sample during the full 5-min cycle. Shown in the chromatogram are the peaks of the perfluorocarbons PMCP, PMCH and PDCH. The approximate retention times from the beginning of the cycle are 0.6 min for PMCP, 1.0 min for PMCH, and 1.7 min for PDCH. The pressure disturbance associated with the start of the next cycle is shown after 5 min. During the next cycle, Trap 2 was analyzed and Trap 1 was in the sample collection mode.

Shown in Figure 2 are the time series plots of the relative tracer concentrations from the September 30 tracer experiment. These relative concentrations were determined by dividing the measured concentrations by the maximum 10-min-average PMCH tracer concentration (average of both traps) measured during

TABLE 1. Dual-Trap Operating Conditions During the 1984 ASCOT Experiments

AMBIENT AIR:
Sampling Duration per Trap - 5 min
Sample Flow Rate - 75 to 325 cc/min

CARRIER GAS:
Type — 5% and 10% H_2-in-N_2
Flow — 40 cc/min @ 40 psig

VALVE SEQUENCE TIMING:

Sequence Step	Duration (min)	Function Trap 1	Function Trap 2
1	0.2	backflush	sample
2	0.4	desorb	sample
3	4.4	backflush	sample
4	0.2	sample	backflush
5	0.4	sample	desorb
6	4.4	sample	backflush

OPERATING TEMPERATURES:

Detector	— 120° C	
Column	— 100° C	
Valves	— 150° C	
Catalyst	— 205° C	
Traps	— 399° C	(during desorb)
	— ambient	(during sampling)

(a) Valco Instruments Inc. Product Name.

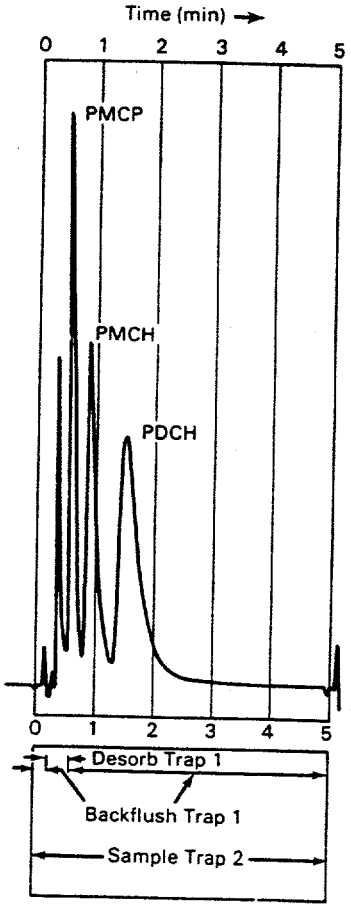

FIGURE 1. Chromatogram of Analysis of Trap 1 While Sample Collection on Trap 2.

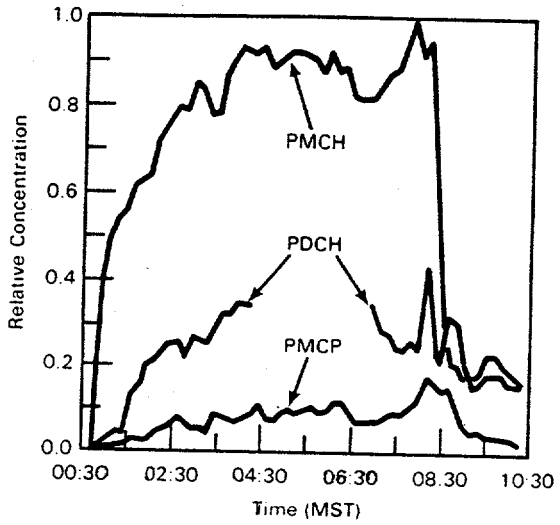

FIGURE 2. Relative Perfluorocarbon Concentrations at the PNL Site During ASCOT Experiment #5 (9-30-84).

the experiment. Ten-min-average values are plotted in Figure 2.

The ground-level tracer (PMCH) released from site 1 reached the PNL site at about 0045 MST (45 min after release start). The concentration climbed to 90% of the maximum measured PMCH concentration by about 0400 MST and stayed here until about 0615 MST. At 0745 MST the maximum PMCH concentration was measured and then by 0815 MST the levels started to decrease rapidly to 20% of the maximum PMCH concentration by about 0845 MST (a five-fold decrease in about 30 min). The increase in PMCH in the morning to a peak at 0745 MST corresponds with the time that the sun was moving across the valley floor. This increase could be caused by the center of the tracer plume moving from the east sidewall to the west sidewall and across the PNL site as the west sidewall became heated by the sun causing a cross-valley circulation. This was observed by Whiteman et al. (1984) during an SF_6 tracer experiment conducted in the same valley during August 1982. The rapid decrease in PMCH after 0815 MST was probably caused by the dilution of the PMCH plume in the growing convective boundary layer and the wind direction reversal from downvalley to upvalley, which occurred at about 0800 MST.

The 220-m release at site 1 (PDCH) and the release at site 2 (PMCP) both showed an increase in concentration from 0730 MST to a peak at 0815 MST and then a decrease after that. This increase in both tracers to a peak at 0815 MST was probably caused by 1) the fumigation to the ground of elevated plumes in a growing convective boundary layer, and 2) the plumes moving from the east sidewall to the west sidewall and across the PNL site, caused by the differential heating of the sidewalls. A segment of PDCH data is not plotted between 0415 and 0700 MST. It was not plotted because of uncertainty in the data caused by release equipment problems on the 220-m release.

Conclusions

The dual-trap perfluorocarbon analyzer provided a dependable means for the real-time measurement of perfluorocarbons. Good separation and sufficient sample size of the three perfluorocarbons, PMCP, PMCH, and PDCH, were attained with a 5-min sample integration and analysis cycle. In addition, the 5-min sample integration time provided the time resolution necessary to show the fumigation of elevated tracer plumes to the ground during the morning transition period. Future data analysis will include comparing the absolute concentrations of the real-time measurements of perfluorocarbons with the ground-level sampling network results and using the meteorological data to interpret the fumigation and ventilation of the tracers during the morning transition period.

Reference

Whiteman, C. D., A. H. Huber, R. W. Fisher, and B. D. Zak. 1984. "Atmospheric Tracer Experiments in a Deep Narrow Valley." In Extended Abstracts, Third Conference on Mountain Meteorology, October 15-19, 1984, Portland, Oregon.

• Coupling/Decoupling of Synoptic and Valley Circulation

The objective of this study is:

To define and develop hypotheses concerning the physical mechanisms by which valley circulations become coupled or decoupled from the larger scale circulations above the valley. The research approach will be based on field studies and application of mathematical models.

SURFACE ENERGY BUDGET COMPONENTS OVER A COMPLEX TERRAIN AREA

M. M. Orgill and C. D. Whiteman

As one component of the 1984 ASCOT field program, five energy balance stations were installed and operated continuously for a period of 3 weeks in Brush Creek valley with the assistance of Dr. Leo Fritschen and Dr. James Simpson of the University of Washington. This article contains a description of the instrumentation and the sites where the stations were installed and a preliminary examination of a small portion of the data base.

The energy balance stations were installed in different vegetative and climatic zones of the valley. Two stations, PNL and WPL, were located on the valley floor at sites where sensible heat fluxes were being measured by other investigators. Vegetation at the PNL site consisted of sagebrush and bunch grass. Vegetation at the WPL site consisted mostly of grasses with a small amount of alfalfa. Two stations were located on sidewalls. The west slope station was approximately 147 m above the PNL valley site. Vegetation consisted of bushes and grasses. The sidewall slope was around 36°. The east slope was around 140 m above the PNL valley site. Vegetation was primarily sagebrush. The slope was around 42°. The last station was located on the ridge crest east of the valley around 672 m above the PNL valley site. Vegetation was primarily sage and oakbrush.

The instrumentation at each site consisted of upward- and downward-facing pyranometers, a pyranometer with shadow band, a net radiometer, a downward-facing total hemispherical radiometer, a soil heat flow transducer at 10 cm depth, a vertical soil temperature sensor with a range of 0 to 10 cm, a wind vane, a three-cup anemometer, and two psychrometers on an automatic exchange mechanism (AEM). With these instruments all the components of the radiation and energy balances were obtained for the five sites.

The vertical temperature and vapor pressure gradients were measured at each station using a pair of fan-aspirated updraft psychrometers that could be physically interchanged at selected time intervals by means of the AEM to reduce sensor bias. The heights of the psychrometers varied between 51 and 227 cm. The recording sensitivity of the psychrometer temperature sensors was 0.006°C and allowed a 40°C temperature range. Cloth wicks were used for the wet bulbs because of the freezing weather conditions.

Signals from the sensors were sampled at 30-s intervals with a 16-analog and 4-digital channel CMOS data collection system. Three 0.5-mA constant current supplies and 5- and 6-V dc regulated outputs were added to the data system. The 5-V regulator supplied the data system while the 6-V regulator supplied the computer discussed below. Primary power was supplied by a 12-V dc deep-cycle RV battery. A small inexpensive personal computer was used at each site to control the AEM and to sample, process, and store the data. Under computer control, raw data were averaged, converted to engineering units, and recorded at 30-min intervals on a cassette tape recorder.

The five portable, battery-operated, energy balance stations were operated in the Brush Creek valley from September 16 through October 6, 1984: for 105 station-days. The stations were installed with the radiation sensors oriented horizontally at all sites. Toward the end of the 3-week period (September 27), the ridge-crest station was decommissioned and reinstalled next to the western sidewall site with the radiometers oriented parallel to the slope. These data

will be used to compare radiation values obtained by the two different methods.

The components of the radiation balance include the net radiation, Q*, the net solar radiation, K*, the net longwave radiation, L*, and the individual short- and longwave components, K↓ and K↑, and L↓ and L↑. The sign convention for these components is defined so that fluxes towards the surface are positive and fluxes away from the surface are negative. An example of the radiation components for the PNL site for a clear day, September 29, is shown in Figure 1. Astronomical sunrise occurred at 0612 MST and sunset occurred at 1754 MST.

The relationships between the radiation components are given by the following equations:

$$Q^* = K^* + L^*$$
$$K^* = K\downarrow + K\uparrow$$
$$L^* = L\downarrow + L\uparrow$$

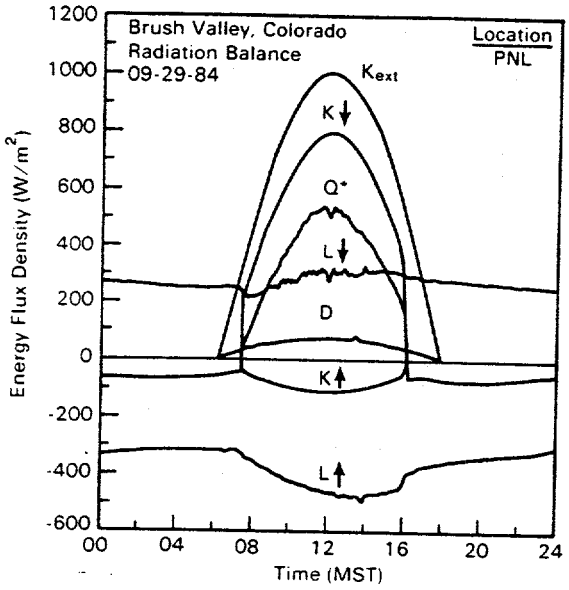

FIGURE 1. Radiation Components for the PNL Valley Site During September 29, 1984.

The downward shortwave radiation, K↓, is composed of two components--the direct beam component, S, and the diffuse beam component, D, so that

$$K\downarrow = S + D.$$

The albedo, or reflectivity, of a surface is given by

$$K^* = -K\uparrow / K\downarrow.$$

During nighttime the individual shortwave components K↑ and K↓ are zero, so that the net radiation is given by

$$Q^* = L^* = L\downarrow + L\uparrow.$$

The radiation components were compared with the extraterrestrial radiation, K_{ext}, calculated by a solar radiation model (Whiteman 1980). K_{ext} is the theoretical radiation on a horizontal surface outside the earth's atmosphere at the latitude and longitude of the experimental site. Tentative results for the five sites for September 29, 1984, are presented in Tables 1 and 2.

This unique data base will be used in comparing radiation and energy balance components for the different sites under different weather conditions, for extrapolating the data from the various sites to the whole valley, and in calculating the energy budget of the valley atmosphere using extrapolated sensible heat and latent heat flux.

Reference

Whiteman, C. D. 1980. Breakup of Temperature Inversions in Colorado Mountain Valleys. Atmospheric Science Paper No. 328, Climatology Report No. 80-2, Department of Atmospheric Science, Colorado State University, Fort Collins, Colorado.

TABLE 1. Daily Radiation Totals, MJ/m²

Site	Q^*	K↓	K↑	K^*	D	L↓	L↑	L^*	K_{ext}
PNL	8.20	19.23	-2.73	16.50	2.10	23.63	-31.93	-8.30	27.26
WPL	8.41	19.34	-3.90	15.44	2.32	23.01	-30.03	-7.02	27.26
E	7.64	19.74	-4.21	15.53	2.49	24.55	-32.44	-7.89	27.26
W	7.77	17.14	-1.95	15.19	3.24[a]	23.98	-31.40	-7.42	27.26
W#2	6.66	15.82	-1.74	14.08	2.46	23.98[b]	-31.40[b]	-7.42	21.14[c]

(a) Shadow band misalignment. Estimated correct value is 2.22.
(b) Assumed equal to values for W. See text.
(c) Slope-parallel K_{ext}; others are for horizontal surface.

TABLE 2. Ratios of Various Radiation Components, September 29, 1984

	Ratios						
					Local SR to Local SS		
Site	K↑/K↓	D/K↓	K↓/Kext	$Q^*/K↓$	$K↓/K_{ext}$	$Q^*/K↓$	Q^*/K_{ext}
PNL	0.14	0.11	0.71	0.43	0.76	0.61	0.47
WPL	0.20	0.12	0.71	0.43	0.77	0.59	0.46
E	0.21	0.13	0.72	0.39	0.79	0.56	0.44
W	0.11	0.13[a]	0.63	0.45	0.77	0.68	0.53
W#2	0.11	0.16	0.74	0.42	0.82	0.67	0.55

(a) Estimated value

Boundary Layer Meteorology in Complex Terrain

BOUNDARY LAYER METEOROLOGY IN COMPLEX TERRAIN

- **Atmospheric Boundary Layer Studies**
- **Atmospheric Diffusion in Complex Terrain**
- **Coupling/Decoupling of Synoptic and Valley Circulation**

Major reserves of fossil fuels are located in mountainous or other complex terrain. As the use of these fuels as an energy source increases, the emission of air contaminants, such as sulfur and nitrogen compounds, trace metals, and fugitive dust produced by the combustion, conversion, and extraction of these fuels, will increase also. The analysis of the fate of these pollutants is particularly difficult in mountainous terrain settings, but is urgently needed to ensure that the nation's energy plan can proceed efficiently and yet be environmentally sound.

The research activities at PNL in this study area are related primarily to the multilaboratory Atmospheric Studies in Complex Terrain (ASCOT) program. A wealth of data from the Geysers and Brush Valley areas are being analyzed and tested against a variety of models accounting for the transport and dispersion of air contaminants under nocturnal meteorological conditions.

Contributions during FY 1984 include the analysis of data from the 1982 Brush Valley experiments to estimate the atmospheric budget for valley drainage winds and further evaluation of winds measured by Doppler sodar. As a result of collaboration initiated with the Meteorlogical Institute of the University of Innsbruck, Austria, Whiteman and Dreiseitl produced the first widely available english translations of four classical papers on alpine meteorology by Wagner, Ekhart and Defant. These papers, plus a description of recent European experience in complex terrain field studies, are available as an ASCOT report and should be of great value in future complex terrain field experiments.

• Atmospheric Boundary Layer Studies

The objectives of these studies are:

To investigate the meteorological characteristics of the planetary boundary layer that pertain to contaminant transport and dry removal.

To analyze the transport and diffusion of contaminants in complex terrain, particularly for the western slope of the Rocky Mountains in Colorado and The Geysers Geothermal Area of California.

To construct simple models for the prediction of the depth, speed, and direction of gravity-controlled drainage flows and of turbulence and contaminant dispersion within these flows.

To examine nocturnal valley flow by developing a simple model for the mass, momentum, and thermal energy budgets in a valley and by taking measurements of valley flow structure.

FURTHER COMPARISONS OF WINDS MEASURED BY DOPPLER SODAR AND THE HMS 120-m TOWER

G. F. Athey and T. W. Horst

A second comparison of the winds measured by a Doppler sodar and the Hanford Meteorological Station 120-m tower was made during the spring of 1984. Half-hourly averages of wind speed and direction were collected over an 18-day period, from March 31 through April 17. The primary purpose of the comparison was to further evaluate the sodar operation.

The initial study (February 1983) used tower wind values obtained from the Hanford forecasters' visual inspection of analog strip charts. For this second comparison, an HP-85 computer was used as the tower data acquisition system. The computer sampled the tower anemometers every 20 s and resolved the winds to better than 0.1 m/s and 1 degree. This method provided a more accurate means of obtaining tower data. However, there remain the inherent differences in how the winds are measured. The tower anemometers measure flow at a fixed point while the sodar measures a volume average.

Measurements were made at four levels above ground: 30.5, 61.0, 91.5, and 121.9 m. The tower was instrumented with cup and vane anemometers. The Doppler winds were obtained from vertical sodar gates 15.2-m wide centered on the four selected levels. The sodar was operated at a base frequency of 2000 Hz with a 50 ms pulse length. The sodar was located about 100 m from the tower; the antennae were positioned so that the beam paths intersected 100 m above the ground.

Figure 1 shows scatter plots for the wind speeds at the four separate levels. The straight line shown has a slope of one and represents the ideal linear relationship. The large scatter of points at the 30.5-m level is similar to results at that level obtained in the earlier comparison (Athey and Horst 1984). The poor linear correlation is probably caused by transducer "ringing" immediately after pulsed transmission. With the present transducers, the problem effectively sets a lower limit of 45 m on measurement of winds. New transducers available from the manufacturer may cure the problem. Except at the 30.5-m (100-ft) level, there is good agreement between the two systems. Below 10 m/s there is a strong linear relationship. However, at the higher wind speeds the sodar values are noticeably lower than the tower values.

The two data sets were analyzed separately and compared. Table 1 presents the summary statistics for the two data sets and their comparison. The correlation coefficient assumes that there is a linear relationship between the values. The data were fit to a straight line using the least-squares method.

For the three upper levels, the mean absolute error is only about 0.5 m/s. The correlation coefficients at these levels are all at least 0.90, which suggests a strong linear relationship. The slopes of the regression lines

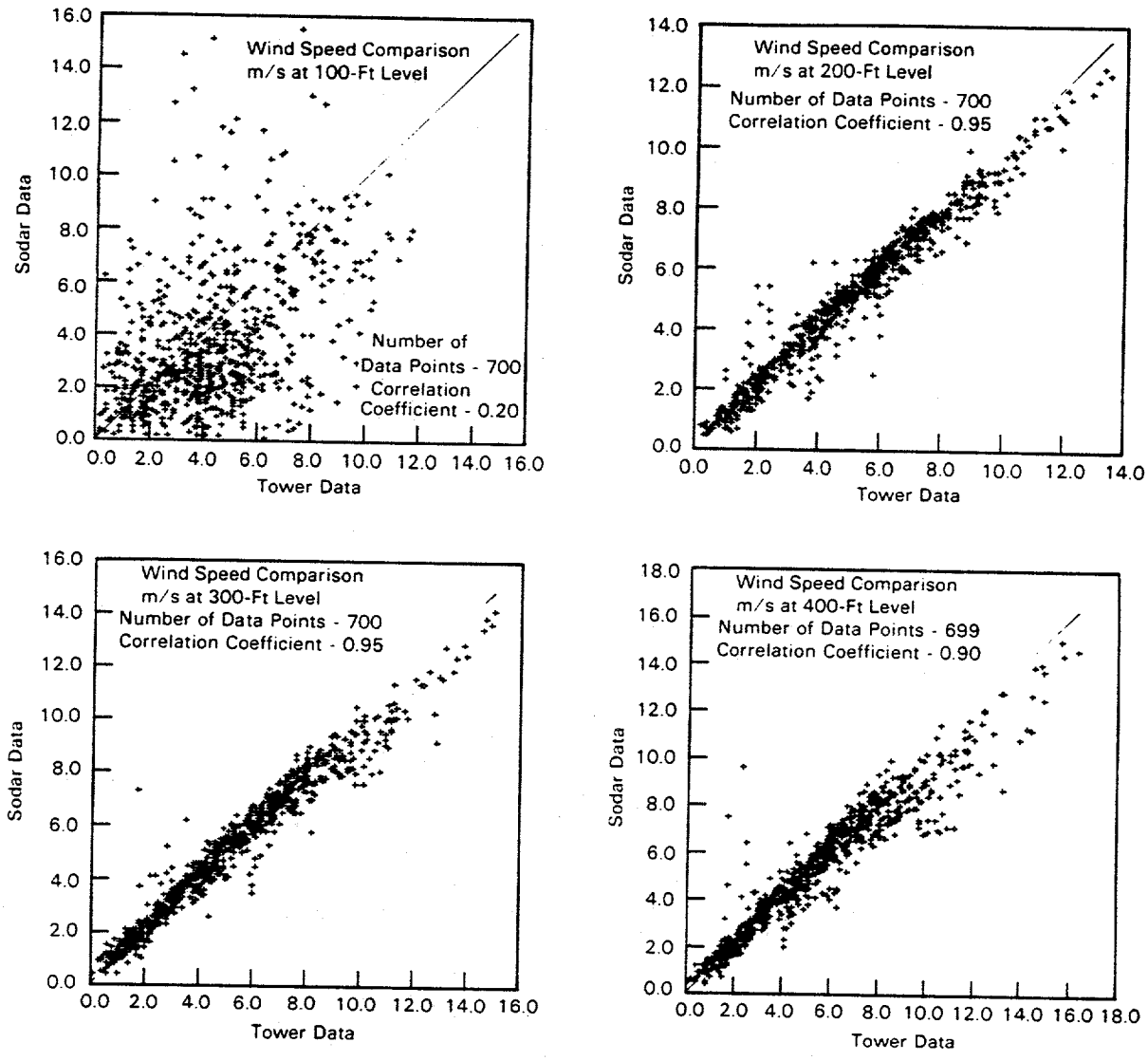

FIGURE 1. Scatter Plots of Sodar vs. Tower Wind Speeds at Four Levels.

reflect the increase with height of the number of low sodar values occurring above 10 m/s.

The tendency of the sodar to under-measure winds above about 10 m/s was an anticipated result. The sodar uses a band-pass filter to minimize the extraneous signals being seen. The filter is 100 Hz wide centered on 2000 Hz. A frequency shift of 50 Hz corresponds to a wind speed of about 14 m/s. Therefore, in high winds, the Doppler shift cannot be properly evaluated by the sodar. The decrease in sodar wind speed is apparent in the half-hourly averages even at average tower speeds as low as 10 m/s. This is probably caused by the inclusion of individual samples greater than 14 m/s within the average. To confirm this, the tower data were filtered to eliminate wind speed pairs where the tower value was greater than 10 m/s. Table 2 shows the results of the comparison with the filtered data.

TABLE 1. Summary Statistics of Wind Speeds Using All Data

	Tower Wind Speed, m/s		Sodar Wind Speed, m/s		Comparison Statistics		Linear Regression Line	
Level, m	Mean	SD	Mean	SD	Mean Absolute Error	Correlation Coefficient	Y Intercept	Slope
30.5	4.27	2.33	3.62	2.55	1.998	0.45	1.54	0.49
61.0	5.06	2.69	5.06	2.50	0.418	0.97	0.48	0.91
91.5	5.51	2.95	5.47	2.69	0.483	0.97	0.58	0.89
120.1	5.68	3.05	5.58	2.71	0.632	0.95	0.77	0.85

TABLE 2. Summary Statistics of Wind Speeds Using Only Data Pairs Where Tower Speeds Were ≤10 m/s

	Tower Wind Speed, m/s		Sodar Wind Speed, m/s		Comparison Statistics		Linear Regression Line	
Level, m	Mean	SD	Mean	SD	Mean Absolute Error	Correlation Coefficient	Y Intercept	Slope
30.5	4.16	2.20	3.57	2.52	1.973	0.41	1.57	0.48
61.0	4.77	2.38	4.80	2.24	0.404	0.97	0.46	0.91
91.5	5.03	2.47	5.07	2.34	0.430	0.97	0.44	0.92
120.1	5.10	2.43	5.14	2.31	0.537	0.94	0.56	0.90

For the 91.5- and 121.9-m levels, filtering decreased the magnitude of the intercept and brought the slope closer to one. With the removal of data pairs out of the sodar's working speed range, the linear fit improved. This linear relationship between the tower and the sodar winds is described as:

$$S_i = a + bT_i + e_i$$

where S_i = sodar reading at time i
T_i = tower reading at time i
e_i = random error at time i (residual).

The residuals are the error between the sodar winds predicted from the fitted regression model and the actual sodar data. In a true linear relationship, the residuals are random, uncorrelated, independent, and normally distributed. The expected values of the sodar wind speeds, based on the tower wind speeds, and the resulting residuals were calculated from both the full and filtered data sets. A plot of the residuals against the expected values for the unfiltered data showed a strong bias. The residuals were not random and uncorrelated. However, a similar plot of the same information from the filtered data showed a much more reasonable distribution (Figure 2).

We are unable to quantify the differences expected from spatial inhomogeneities in the wind flow and the differences from measurement technique variations. The observed agreement between the two systems suggests that the sodar is performing quite well within its known limitations. Although these tests are over a limited height range, the winds measured at higher altitudes are presumably determined with similar accuracy because the measurement process is the same.

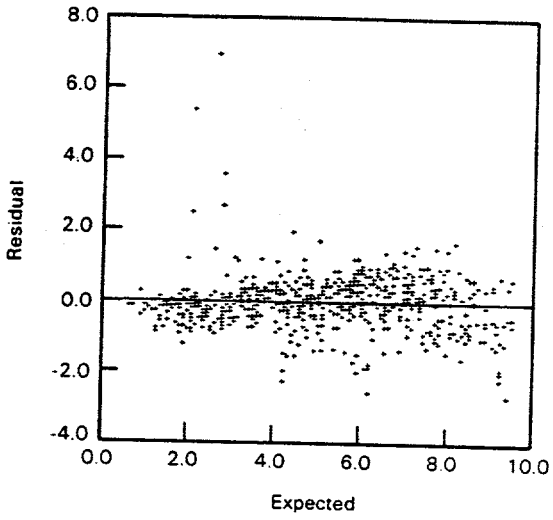

FIGURE 2. Residuals Versus Expected Values for Wind Speeds /10 m/s at 400 ft Level.

Further plans for improving and testing the operation of the Doppler sodar include

1. comparison of winds measured by the sodar and a tethersonde during the 1984 ASCOT experiment

2. installation and testing of more powerful transducers to improve the altitude coverage

3. software development to improve the utilization of marginal data in determining the winds over long averaging times.

Reference

Athey, G. F. and T. W. Horst. 1984. "Comparison of Winds Measured by Doppler Sodar and the HMS 120-meter Tower." In Pacific Northwest Laboratory Annual Report for 1983 to the DOE Office of Energy Research: Part 3 - Atmospheric Sciences. PNL-5000 PT 3, Pacific Northwest Laboratory, Richland, Washington.

• Atmospheric Diffusion in Complex Terrain

Objectives of this study are:

To assist a multi-laboratory program studying diffusion in complex terrain by providing methodologies and techniques for analyses of transport and diffusion over a variety of complex landforms.

To evaluate and develop various transport and dispersion models for complex terrain.

TURBULENT MIXING AND DRAINAGE CONDITIONS

M. M. Orgill and R. I. Schreck

The PNL ASCOT group has been using the Geysers ASCOT data base to examine the effect of large-scale (synoptic and mesoscale) wind systems on the development and persistence of local drainage conditions at the Geysers Geothermal Area. These analyses are a continuation of past work reported by Orgill, Schreck, and Whiteman (1981) and Orgill and Schreck (1984).

This article examines the role of turbulent mixing in the disruption of the nighttime stable layer and drainage conditions over the slope in the Anderson Creek area in the Geysers. An examination of tower and tethered balloon data from the July 1979 and September 1980 experiments shows that the stable inversion layer was subjected to relatively strong (5 m/s or more) upper-level westerly or easterly winds on seven of the nights. Various degrees of erosion of the stable layer on the slope were caused in part by turbulent mixing.

To examine the role of turbulent mixing on the Anderson Creek temperature structure and drainage flow, a modification in a subroutine of the BUDPLT computer program (Whiteman et al. 1984) was used to calculate average profiles of the gradient Richardson number and a stability ratio. The calculations used tethered balloon data from three locations--PDC-1, Unit 19, and Thorne-7--for selected experimental nights. The program calculated average profiles of temperature, potential temperature, and up- or down- and cross-slope wind components. Between 7 and 10 tethered balloon ascent profiles during the time period 2100 PST to 0500 PST were used to compute the averages. The average potential temperature and wind profiles were used to compute average nighttime profiles of the gradient Richardson number (Ri) and stability ratio (SR):

$$Ri = \frac{g}{\bar{\theta}} \frac{\partial\bar{\theta}/\partial Z}{\left(\frac{\partial\bar{u}}{\partial Z}\right)^2 + \left(\frac{\partial\bar{v}}{\partial Z}\right)^2} \qquad (1)$$

$$SR = \frac{\bar{\theta}_{z_2} - \bar{\theta}_{z_1}}{\bar{U}^2} \left[{}^{0}Cs^2/cm^2\right] \qquad (2)$$

where $\bar{\theta}$ is average potential temperature, $\bar{u}$ and $\bar{v}$ are average up- or down- and cross-slope wind components, and $\bar{U}$ is the average wind speed between two heights. Average values of Ri and SR were obtained by differencing over 25-m intervals.

In regions of strong wind shear, considerable turbulent mixing is expected and is revealed by the value of the Richardson number or similar parameter. Table 1 shows the range of average Ri and SR for selected nights during which tethered balloon data were consistently available at two sites for July 1979 and September 1980. Five of the nights (July 18-19, July 24-25, September 11-12, September 19-20, and September 24-25) were classified as good drainage nights. The larger average Ri and SR for these nights show the predominant influence of the stable drainage layer. Three other nights (July 22-23, September 15-16, and September 18-19) were fair or marginal drainage nights. The lower range of average values of the Ri and SR for these nights reflects the greater ambient turbulent mixing. An example of the vertical profile of the average Ri and SR for the night of September 15-16 at Unit 19 and Thorne-7 is shown in Figure 1. A decrease of both the Ri and SR values with height is characteristic of the stronger east winds and turbulent mixing present this night in the upper

TABLE 1. Range of Average Ri and SR for Different Experimental Nights, July 1979 and September 1980

Date	PDC-1		Unit 19		Thorne 7		Drainage Rating
	Ri	SR	Ri	SR	Ri	SR	
1979							
7/18-19	0.2 - 4	0.1 - 2	—	—	1 - 200	2.5 - 40	4
7/22-23	0.2 - 2	0.1 - 2	—	—	0.2 - 10	0.1 - 10	2
7/24-25	1.5 - 2.5	2 - 7.5	—	—	0.4 - 25	0.8 - 20	4
1980							
9/11-12	—	—	0.8 - 150	0.2 - 70	0.8 - 90	0.8 - 30	5
9/15-16	—	—	0.1 - 4	0.1 - 15	0.02 -20	0.1 - 30	3
9/18-19	—	—	0.03 - 5	—	0.06 - 6	—	1
9/19-20	—	—	0.7 - 500	2 - 35	1.5 - 15	0.7 - 30	5
9/21-22	—	—	0.01 - 0.7	—	0.008 - 1.2	—	0
9/22-23	—	—	0.01 - 2.6	—	0.006 - 6.3	—	0
9/24-25	—	—	0.07 - 500	2 - 35	0.3 - 300	1 - 30	5

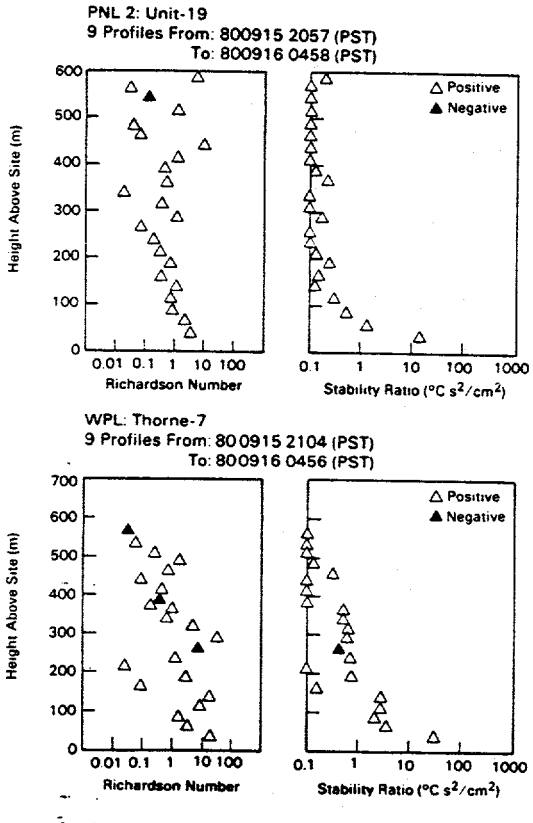

FIGURE 1. Average Richardson and Stability Ratio Number Profiles for Unit 19 and Thorne-7 During Nighttime Hours of September 15-16, 1980.

levels. However, drainage conditions at the surface and downslope were not significantly disturbed on this night.

The full extent of the effects of strong winds and associated resonant topographic waves and turbulent mixing on drainage conditions was evident in the events that transpired on the evenings of September 18-19, 21-22, and 22-23. The low average values of Ri over the slope (Table 1) for these nights show that turbulent mixing was generally high and unfavorable for good temperature inversion and drainage development.

Additional analysis of the tethered balloon data and other ASCOT data could prove valuable in terms of a complete description of dissipation events and in understanding the physical mechanisms that govern these events. This information should be useful in developing and evaluating models, understanding the initial spread of forest fires in mountainous terrain and evaluating transport and diffusion.

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• Coupling/Decoupling of Synoptic and Valley Circulation

The objective of this study is:

To define and develop hypotheses concerning the physical mechanisms by which valley circulations become coupled or decoupled from the larger scale circulations above the valley. The research approach will be based on field studies and application of mathematical models.

ATMOSPHERIC MASS BUDGET FOR BRUSH VALLEY, COLORADO

C. D. Whiteman

In the summer of 1982, the ASCOT program conducted a series of meteorological experiments in the Brush Creek valley of western Colorado. The 650-m-deep Brush Creek valley of Colorado is a 25-km-long side-valley that flows into the Roan Creek valley, 55 km NNE of Grand Junction, Colorado. The valley has nearly ideal topography for initial experiments in complex terrain meteorology. It has a nearly straight, NW-SE axis with uniform, steep (30 to 40°) sidewalls and no major tributaries.

Hourly tethered balloon soundings were conducted in the valley from up to seven sites (Figure 1) on the experimental night of July 30-31, 1982, to investigate the nocturnal mass budget of the valley. A conference paper written by Whiteman and Barr (1984) provides details of the mass budget calculations, which are summarized below.

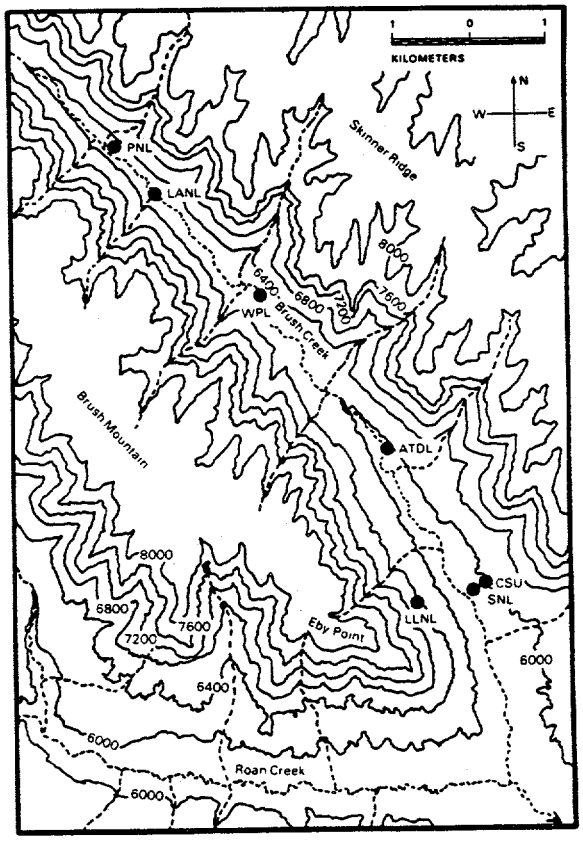

FIGURE 1. Topographic Map of the Brush Creek Valley, with Tethered Balloon Sites Indicated. Contour interval 400 ft (122 m).

Analyses

The goal of the analyses was to estimate how atmospheric mass (or volume) flux across valley topographic cross sections would change with distance down the valley. Volume fluxes were calculated for each cross section of the valley by multiplying the along-valley wind speed component on that cross section by the cross-sectional area. The cross-sectional area of the valley increases strongly with down-valley distance. Vertical profiles of the observed along-valley wind speed components at the individual sites are shown in Figure 2. The characteristics of the nocturnal winds in the deep valley are clearly seen in these profiles. A "jet" occurred in the profiles with maximum wind speeds of 5 to 8 m/s at heights of 100 to 150 m. Down-valley winds increased rapidly from the surface to the peak of the jet, with winds decreasing more slowly above the jet to zero at about ridgetop level. The jet winds decreased somewhat in strength and rose in AGL height with down-valley distance, but there

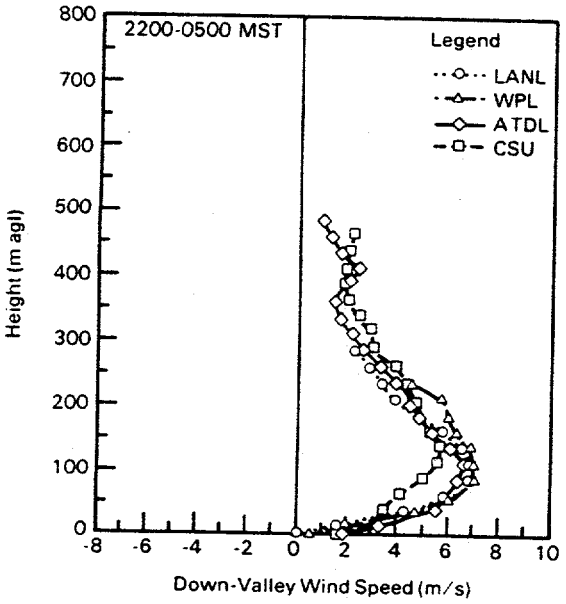

FIGURE 2. Average Down-Valley Wind Speed as a Function of Height for Four Tethered Balloon Sites.

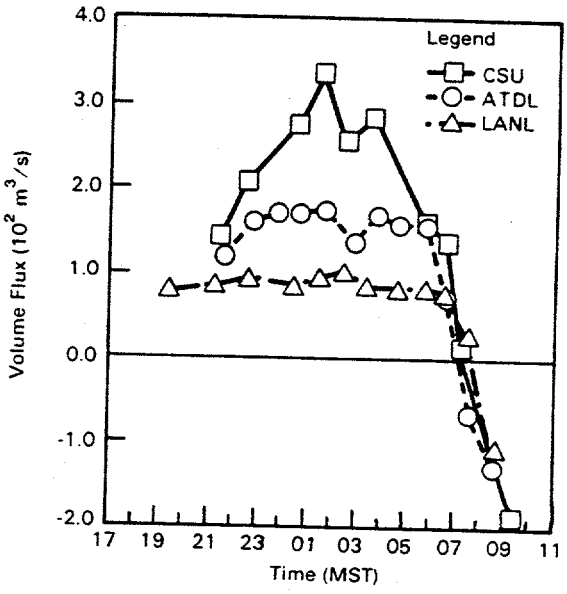

FIGURE 3. Total Volume Flux Across Valley Cross Sections at the CSU, ATDL, and LANL Sites as a Function of Time.

was surprisingly little variation in the profiles at the different sites, even though the valley widens appreciably with down-valley distance.

Figure 3 shows the total volume flux (extended to ridgetop level) for the CSU, ATDL, and LANL sites, plotted as a function of time. The nocturnal flux at the LANL site is about 0.9 x 10^6 m^3/s, at the ATDL site 1.7 x 10^6 m^3/s, and at the CSU site 2.8 x 10^6 m^3/s. Note that at the CSU site, located just above the mouth of the Brush Creek valley, there was a relatively large hourly variation in volume flux during the night.

The results of the analysis (Table 1) clearly show that the nocturnal volume flux across Brush Creek valley cross sections increases with down-valley distance. The divergence of volume flux between valley cross sections was 170 m^3/s per meter of distance along the valley axis in the ATDL-LANL valley segment and 478 m^3/s in the CSU-ATDL segment. Volume flux divergence between the CSU and LANL cross sections was 271 m^3/s per m of distance along the valley floor.

TABLE 1. Calculations of Volume Flux Divergence

Site	Volume Flux Difference (10^6 m^3/s)	Distance (km)	Volume Flux Divergence (m^2/s)
ATDL-LANL	1.7 to 0.9	4.7	170
CSU-ATDL	2.8 to 1.7	2.3	478
CSU-LANL	2.8 to 0.9	7.0	271

Rao (1970), in his studies of three Vermont valleys varying in depth from 300 to 800 m, found nocturnal volume flux divergences from 100 to 300 m^3/s per meter--a finding consistent with our results, except for the higher value observed on the CSU-ATDL valley segment.

The source of the additional volume flux with down-valley distance is of interest. If the source is assumed to be the slope flows, and we use the 5% rule (i.e., the depth of the downslope flow on a valley sidewall is 5% of

the height difference between the site of interest and the ridge top), we can calculate that the 30-m slope flows on the two valley sidewalls must have average downslope flow speeds of 5 m/s. This flow is much higher than would be expected. Furthermore, the slope flows do not provide a new source of atmosphere volume, since they entrain ambient air adjacent to the slope, which is already within the valley.

If we assume that the additional volume (mass) comes from above the valley, we can calculate the mean sinking rate resulting from entrainment over the top of the valley volume. Since the width at the top of the valley is about 2 km and the volume flux divergence is 271 m^2/s, the sinking rate is 0.14 m/s.

Conclusions

Strong, nocturnal, down-valley winds occur in the deep, narrow, Brush Creek valley of Colorado. These winds take the form of a "jet" with peak speeds of 5 to 8 m/s at heights of 100 to 150 m above the valley floor. The wind profiles above the valley center change only slightly with down-valley distance in the lowest 10 km of the valley, while the cross-sectional area of the valley increases sharply. Since the along-valley wind is approximately horizontally homogeneous on a valley cross section, the result is an increase with down-valley distance of volume (or mass) flux across valley cross sections. This divergence of volume flux is approximately 270 m^3/s per meter of distance down the valley. Divergence requires that mass be entrained into the valley from above to conserve mass. Calculations show that resulting subsidence at the top of the valley would be at the rate of 0.14 m/s.

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SUMMARY OF EUROPEAN COMPLEX TERRAIN METEOROLOGY EXPERIMENTS

C. D. Whiteman

The present theories of valley and slope wind systems in areas of complex terrain rely on observations and theoretical bases developed by investigators in the Alps in the 1930s and 1940s. Most of the original research papers describing this work were published in German and French in journals that are difficult to find in the U.S. No translations of these articles have been generally available, so that few meteorologists working in the field of mountain meteorology have actually read the original papers that form the very basis of our current understanding of valley meteorology.

In 1984, Whiteman and Dreiseitl (1984) produced the first widely available English translations of four classical papers in alpine meteorology, written by A. Wagner (1938), E. Ekhart (1944, 1948), and F. Defant (1949).

Wagner's 1938 paper forms the basis of the now-accepted theory of along-valley wind systems. In that paper, Wagner explains their relationship to along-slope wind systems, backs the theory with observations, and explains the topographic reason for anomalous winds like the ones at Trento, Italy, which had been cited earlier as evidence of a wind system operating in apparent contradiction to his theory.

Ekhart's two papers (1944 and 1948), published after Wagner's death, present experimental evidence that supports Wagner's theories. The 1944 paper deals with aerological observations of valley winds in the Salzach and Lammer valleys of Austria. The 1948 paper presents the results of a series of temperature measurements that allowed, for the first time, the direct testing of Wagner's (1938) theory on the thermal origin of the diurnal along-valley wind systems.

Defant's (1949) paper provides a summary of the knowledge of slope winds. It reviews Wagner's (1938) theory and presents the now well-known set of idealized diagrams illustrating the time and space relationship between the along-slope and along-valley wind systems. He uses composited aerological observations collected by Riedel on the south-facing slope above Innsbruck during both up-slope and down-slope flow periods to show that Prandtl's (1942) steady-state theory of slope currents can explain many of the features of the observations. Defant then extends Prandtl's theory to treat nonstationary conditions.

A short introduction to Whiteman and Dreiseitl's (1984) translations summarizes four recent Alpine meteorology field experiments, emphasizing ongoing research that extends the research of Wagner, Ekhart, and Defant. The four experiments include Innsbruck Slope Wind Experiment of 1978, the MESOKLIP Experiment of 1979, the DISKUS Experiment of 1980, and the ALPEX/MERKUR Experiment of 1982. A large number of references are provided in the introduction so that English-speaking meteorologists can access the important work conducted in the Alps in the last 10 years.

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Dispersion, Deposition and Resuspension of Atmospheric Contaminants

DISPERSION, DEPOSITION, AND RESUSPENSION OF ATMOSPHERIC CONTAMINANTS

- **Dry Deposition**
- **Oil Shale Fugitive Air Emissions**
- **Particle Resuspension and Translocation**
- **Theoretical Studies and Applications**
- **Processing of Emissions by Clouds and Precipitation**

The concentration of contaminant species in air is governed by the rate of input from sources, the rate of dilution or dispersion as a result of air turbulence, and the rate of removal to the surface by wet and dry deposition processes. Once on the surface, contaminants also may be resuspended, depending on meteorological and surface conditions. An understanding of these processes is necessary for accurate prediction of exposures of hazardous or harmful contaminants to humans, animals, and crops.

At PNL several research programs focus attention on these processes through a combination of field, laboratory, and modeling studies. In the field, plume dispersion and plume depletion by dry deposition are studied by the use of tracers. A unique application of tracer technology at PNL is the simultaneous release of depositing and nondepositing tracers. Dry deposition was investigated for particles of both respiration and inhalation interest. Complementary dry deposition studies of particles to rock canopies were conducted under controlled conditions in a wind tunnel. Because of increasing concern about hazardous, organic gases in the atmosphere some limited investigations of the dry deposition of nitrobenzene to a lichen mat were conducted in a stirred chamber.

Resuspension is also studied using tracers and contaminated surfaces and in the wind tunnel. The objective of the resuspension studies is to develop and verify models for predicting the airborne concentrations of contaminants over areas with surface contamination, develop resuspension rate predictors for downwind transport, and develop predictors for resuspension input to the food chain. These models will be of particular relevance to the evaluation of deposition and resuspension of both radionuclides and chemical contaminants.

In FY 1984, initial plans for the new initiative program, Processing of Emissions by Clouds and Precipitation (PRECP), as a part of the National Acid Precipitation Assessment Plan (NAPAP) were developed. The program focuses on the scavenging of energy contaminants, particularly those leading to the formation of acids, through extensive field measurements. Near-term program plans are summarized in this report.

• Air Pollution Dry Deposition

Objectives of this study are:

To develop model predictors for dry deposition velocities as a function of pollutant and deposition surface properties and atmospheric variables.

To investigate dry deposition processes in field and wind tunnel experiments using tracers.

To investigate dry deposition in field experiments through the use of multiple tracers to obtain area-averaged dry deposition removal rates.

To investigate dry deposition processes in wind tunnel experiments.

DRY DEPOSITION OF NITROBENZENE TO A LICHEN MAT

G. A. Sehmel and R. N. Lee

Although organic gases are emitted to the atmosphere during energy conversion processes, the removal of gaseous organic air pollutants by dry deposition has not been investigated extensively for natural surfaces in the environment. There are some dry deposition velocity data for peroxyacetyl nitrate (PAN, 0.8 cm/s, summarized by Sehmel [1980]), methyl iodide (10^{-4} to 10^{-2} cm/s), and carbon tetrachloride (10^{-4} cm/s, see Cupitt [1980]).

This article reports a limited investigation of nitrobenzene deposition on a lichen mat in a stirred chamber. A lichen mat was selected as the deposition substrate since lichens are ubiquitous in the environment and may represent a significant low-profile deposition surface in arid regions. A second stirred chamber that had water on its floor, instead of a lichen mat, was used to simultaneously investigate effects of moisture on observed loss rates.

The experiment reported here is an extension of previous dry deposition investigations in which we used stirred chambers to investigate dry deposition velocities for deposition substrates representative of building materials. In these prior investigations, the organics investigated were nitrobenzene and perchloroethylene and the building materials were cement, vinyl asbestos tile, and tar paper. In all cases the building materials were dry. Measured deposition velocities in the prior experiments were significantly less than those usually reported for inorganic gases. Deposition velocities were low, and ranged from 4×10^{-6} to 6×10^{-4} cm/s. Nitrobenzene was selected for investigation in the following experiments since dry deposition velocities might be greater for nitrobenzene, which has a lower vapor pressure than perchloroethylene.

Experimental Procedures

Dry deposition velocities were investigated using two identical stirred chambers: one chamber is shown schematically in Figure 1. A three-bladed fan, with 18 in.-diameter blades and a 25° pitch, was located centrally in the top of the chamber. The fan speed was held constant at 520 rpm. The supporting structure was constructed with wooden two-by-fours and plywood. The walls, ceiling, and floor are 5-mil Teflon® sheeting. The stirred chamber is hexagonal with an internal height of 74 cm and internal side lengths of 152 cm. The maximum internal horizontal dimension is 304 cm, the internal volume is 4.4 m^3, and the floor area is 6.0 m^2. The floor was covered with a lichen mat from the Horn Rapids Dam area at Hanford.

Both nitrobenzene and an inert tracer gas, SF_6, were introduced into the stirred chamber. Samples were extracted through septa as a function of time, and concentrations evaluated using gas chromatographic (GC)

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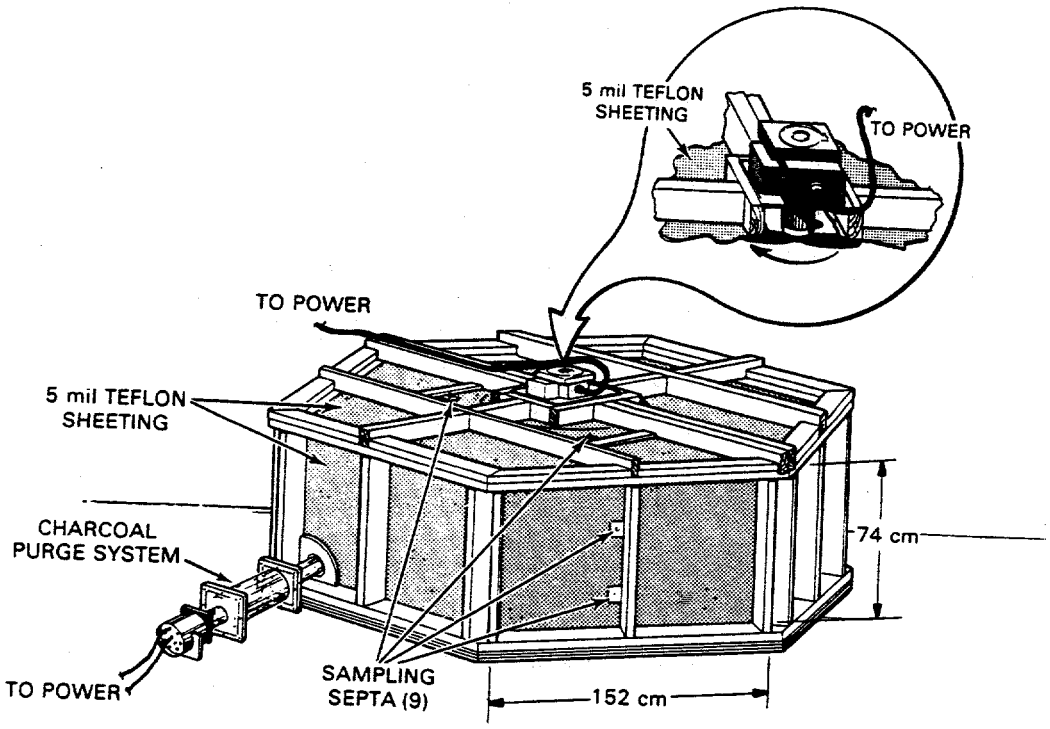

FIGURE 1. Schematic of a Stirred Chamber.

techniques. Nitrobenzene samples were collected by pulling chamber air through a silica gel adsorption tube using an air sampling pump. The mass of material collected was obtained by solvent extraction of the adsorbent followed by GC analysis, and the volume of air sampled was used to calculate the average nitrobenzene concentration during the sampling interval. The SF_6 was used to evaluate leakage rates. Both nitrobenzene and SF_6 concentrations tended to decrease exponentially with time. Least-squares techniques were used to evaluate the average losses (in percent per hour).

Dry Deposition Velocity Calculations

Dry deposition velocities for nitrobenzene are calculated from the differences in loss rates (nitrobenzene - SF_6), with the assumption that stirring produces uniform gas concentrations within the chamber and that wall losses are negligible. In this case, the dry deposition velocity is

$$v_d = (1/A)\,[V(\text{difference in loss rates})]$$

$$= [1/(6.0 \times 10^4\ cm^2)]\,[(4.4 \times 10^6\ cm^3)(\text{percent loss/h})]/[100 \times 3600]$$

$$= (2.0 \times 10^{-4})(\text{percent loss/h}) \qquad (1)$$

where v_d is the deposition velocity in cm/s, A is the chamber floor area in cm^2, and V is the chamber volume in cm^3.

Results

Test conditions, gas loss rates, and deposition velocities are summarized in Table 1. The deposition surfaces were an empty dry chamber, an empty chamber containing pools of water, and a lichen mat in the chamber. In the deposition velocity calculations, we assumed that the water pools covered the bottom of the chamber; however, there were only 1500 cm^3 of water pooled on the chamber floor.

TABLE 1. Nitrobenzene Dry Deposition Velocities

Exp. date	Exp. no.	Deposition Surface	Measured losses (%/h) nitrobenzene	Measured losses (%/h) SF_6	Calculated nitrobenzene loss rate (%/h)	Deposition Velocity (cm/s)
6/19	23-1	empty chamber	7.87	5.60	2.27	4.5×10^{-4}
7/31	24-1	empty chamber	9.50	5.88	3.62	7.2×10^{-4}
6/14	22-1	water pools	24.8	4.64	20.2	4.0×10^{-3}
6/19	23-2	water pools	35.5	10.2	25.3	5.1×10^{-3}
6/11	21-2	lichen mat with condensation on walls	42.6	5.24	37.4	7.5×10^{-3}
7/31	24-2	damp lichen mat with no visible condensation	36.8	6.12	30.7	6.1×10^{-3}

Conclusions

The calculated dry deposition velocities reflect mostly substrate resistance to mass transfer of nitrobenzene. Resistances for water and lichen mat surfaces are significantly less than for the dry building materials previously investigated. For example, for tile and tar paper the calculated nitrobenzene loss rates were small, ranging from less than detectable up to 2.96%/h. In comparison, loss rates reported here are an order of magnitude greater and range from 20.2 to 37.4%/h.

Since loss rates for nitrobenzene, a slightly soluble compound, are affected significantly by the presence of surface water, the conclusion is made that dry deposition velocities for gases are very dependent upon the surface water available for dry deposition removal. Since condensation on the chamber surfaces could have occurred when water was in the chamber, the relative deposition into the free water pools and onto the chamber surfaces must be estimated. Limited data suggest that the water pools were saturated with nitrobenzene at the end of an experiment. The ratio of nitrobenzene concentration in the water divided by the concentration in air (62.6 ng/ml water divided by 37.5 $\mu g/m^3$ air) was 1.7×10^3. The nitrobenzene in the water pools cannot entirely account for the loss of nitrobenzene from the vapor phase.

Dry deposition velocities for a dry lichen mat can be estimated from the differences in gas loss rates for the water pools and the lichen mat. Calculated nitrobenzene loss rates for the lichen mat ranged from 30.7 to 37.4%/h, and were greater than loss rates for water surfaces, which ranged from 20.2 to 25.3%/h. If the difference range from 4.4%/h (30.7 to 25.3) to 17.2%/h (37.4 to 20.2) is attributed to deposition onto a dry lichen mat, the corresponding dry deposition velocities range from 8.8×10^{-4} to 3.4×10^{-3} cm/s. Dry deposition velocities for a dry lichen mat are greater than for the upper limit of 5.9×10^{-4} cm/s for dry tile and tar paper.

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DRY DEPOSITION THROUGH A THREE-LAYER ROCK CANOPY

G. A. Sehmel and W. H. Hodgson

Particle dry deposition velocities can be estimated as a function of dimensionless parameters from a correlation based on wind tunnel experiments (Sehmel 1984, Sehmel and Hodgson 1980); this correlation considers the effects of particle diameter, friction velocity, and aerodynamic surface roughness. However, effects of deposition-canopy depth on deposition velocities were not investigated in the previous wind tunnel experiments, and have not been generalized from field experimental results (Sehmel 1980).

The distribution of dry deposition throughout the depth of the deposition canopy is one of the significant uncertainties in the predictions of, or evaluation of, dry deposition. The objectives here were to investigate dry deposition of particles as a function of depth in a canopy and to expand the data base for particle dry deposition velocities evaluated with control of experimental conditions.

The dry deposition canopy investigated in wind tunnel experiments was a three-layer rock canopy that had been used in investigations of wind resuspension from underlying soil (Sehmel and Hodgson 1985). This canopy was selected for investigation since air flow penetrated through the three layers of rock and caused resuspension from the underlying soil. This same air flow penetration should also transport depositing particles and cause deposition throughout the depth of the rock canopy.

Experimental Procedures

The deposition surface consisted of three layers of rock, placed in a close-packed array in a wind tunnel. The rock was river rock, from a 1.2- to 2.5-cm (0.5- to 1-in.) screen size. A 7.2-m length of the wind tunnel floor was covered with river rock.

Dry deposition was investigated with monodisperse diameter particles (6 μm diameter uranine particles) produced with a spinning disc aerosol generator. Reported here are dry deposition velocities and particle penetrations as a function of depth at a test section located at 6.1 m. The test section was 20 cm wide by 28 cm long, centrally located in the wind tunnel cross section of 61 by 61 cm (2 by 2 ft). The rocks in the test section were placed on a 20 by 28 cm section of aluminum foil, which was removable to evaluate percentages of depositing particles that penetrated across all three layers of rock.

Average heights of the rock layers are listed in Table 1.

Particle penetration through the rock canopy was evaluated by washing deposited uranine particles from each layer of rock (an average of 131 rocks in each layer) and the underlying aluminum section. Dry deposition velocities were calculated from the total deposition to all layers of the test section and from airborne concentrations measured by isokinetic sampling at 10.4 cm above the wind tunnel floor [i.e., an average of 5.6 cm (10.4 - 4.8 cm) above the average rock height]. Wash solutions were analyzed fluorimetrically for uranine content.

Friction velocity (u_*), displacement height (d), and aerodynamic surface roughness height (z_o) were evaluated from measurements of wind speed (u) as a function of height (z) with a pitot tube. A sloping manometer was used for accuracy of wind speed measurement. Wind speeds as a function of height were fitted by least-squares techniques to the equation

$$\frac{u}{u_*} = \frac{1}{k} \ln[(z - d + z_o)/z_o] \quad . \qquad (1)$$

The negative sign in front of the displacement height was required since heights were referenced to the wind tunnel floor and since wind speeds above the rocks were a function

TABLE 1. Height of Rock Canopy Layers

Rock Layer	Height From Wind Tunnel Floor, cm: Average Height of Most Rocks	Height From Wind Tunnel Floor, cm: Maximum Height from Flat Metal Placed on Top of the Rock Layer
Top	4.8	6.0
Middle	3.4	3.7
Bottom	1.7	2.3

of the near rock-surface height. Wind speeds were fitted to data between heights for which Equation 1 is applicable. Calculated wind speed profile parameters are listed in Table 2 for the five wind speeds investigated. Because of pitot-tube small pressure differences at the lowest wind speed investigated, there are considerable uncertainties in the listed parameters for a friction velocity of 30 cm/s.

Results

Dry deposition velocities for 6-μm diameter particles are shown in Figure 1 as a function of friction velocity. Dry deposition velocities are all significantly greater than the 2×10^{-1} cm/s gravitational settling velocity for 6-μm diameter particles of density 1.5 g/cm^3. Dry deposition velocities increase rapidly as friction velocity increases. If a power law is assumed for the increase, u_*^n, the exponent n is equal to 2.4.

Since dry deposition velocities continue to increase with increasing friction velocity, any effects of simultaneous resuspension are not apparent even for the highest friction velocity investigated of 83.3 cm/s (corresponding to a maximum wind speed in the wind tunnel of 14 m/s).

The relative location of depositing particles within the rock canopy can be represented by the percentage penetration of all depositing particles that are transported onto, or below, each layer of rock. Percentage

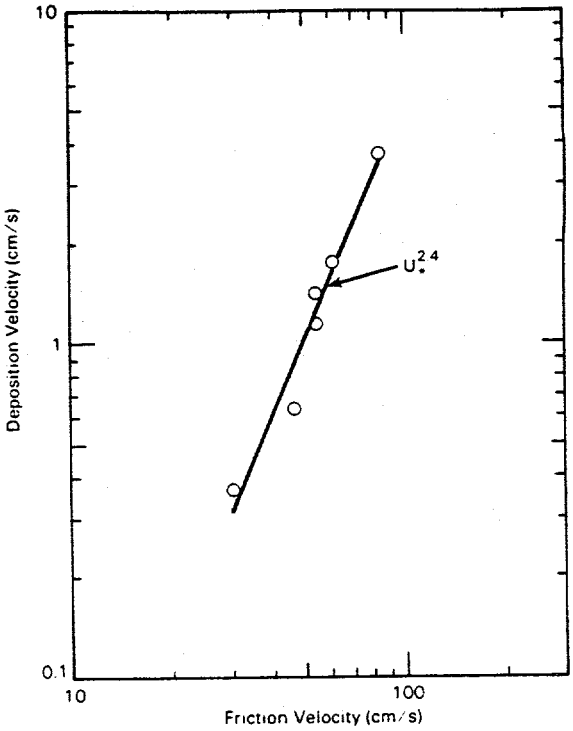

FIGURE 1. Dry Deposition Velocities for 6 μm Diameter Particles Onto a Three-Layer River Rock Surface, 1.2 to 2.5 cm Screen Size.

penetration is shown in Figure 2 as a function of friction velocity for penetration onto, or below, the middle and bottom rock layers, and onto the underlying surface.

Penetration onto the lower layers of the rock canopy was significant. From 35 to 66% of the depositing particles were deposited below the top layer of rock, and from 4 to 16% were transported to the underlying surface.

There appears to be a critical friction velocity of about 48 cm/s, which affects penetration. Penetration decreases for friction velocities greater than critical. The decrease is approximated in the figure with lines proportional to $u_*^{-2.5}$.

Penetration data are shown in Figure 3 as a function of height above the wind tunnel floor. Data are plotted at the average top-of-rock height for each layer. Penetration for each friction velocity appears to follow an exponential decrease with with distance.

TABLE 2. Wind Speed Parameters During Reported Dry Deposition Velocity Measurements

Friction Velocity, cm/s	Aerodynamic Surface Roughness Height, cm	Displacement Height, cm	Height Limits For Fitting Equation 1, cm
30.0	1.2	0	5.4 to 23
46.5	0.27	3.2	5.4 to 13
54.0	0.098	3.7	5.4 to 13
60.6	0.060	3.8	5 to 23
83.3	0.046	3.8	5 to 33

When an exponential relationship is applied, exp (n*z), for each friction velocity, the parameter n ranges from 0.40 to 0.66.

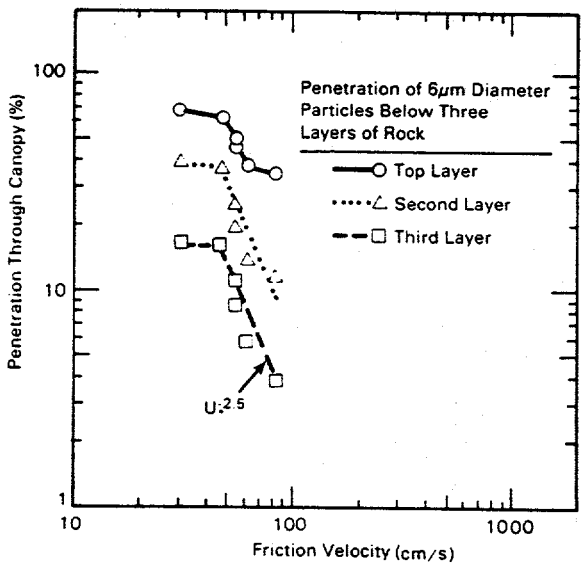

FIGURE 2. Particle Penetration Through a Three-Layer River-Rock Surface as a Function of Friction Velocity for Constant Penetration Heights.

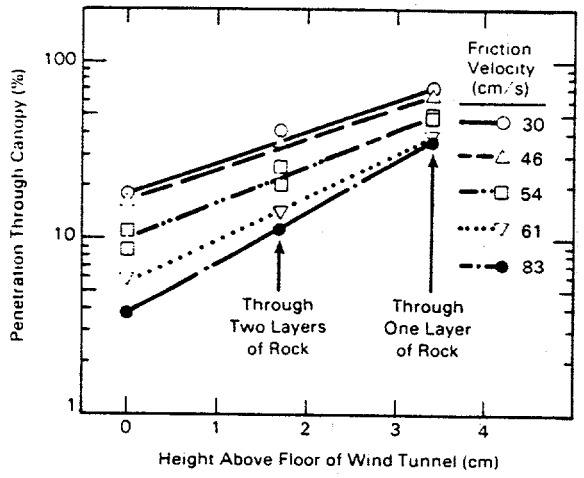

FIGURE 3. Particle Penetration Through a Three-Layer River-Rock Surface as a Function of Penetration Heights for Constant Friction Velocities.

Conclusions

The combined effects of deposition, diffusion, and resuspension within the canopy are represented by exponential decreases in particle penetration with distance into the rock canopy. Some particles deposit on the surface underlying three layers of rock. These results support the concept that particle transport can be significant even though air is slowly moving within a canopy. As previously stated, this air motion is also sufficient to suspend particles from the underlying soil.

Although penetration decreases, significant deposition occurs below the upper layer of rock. If these results can be generalized to dense vegetative canopies such as forests, significant dry deposition is expected to occur within the lower portions of a vegetative canopy even though wind speeds are low.

If these results can be extrapolated to vegetative canopies, the difficulty of obtaining dry deposition velocities by sampling vegetative canopies is emphasized. Large numbers of vegetative and underlying surface samples would be required to adequately determine the total dry deposition flux to a vegetative canopy. This is one reason that the dual-tracer technique is being developed (Sehmel 1983a, 1983b, 1985) in order to evaluate the integrated effects of area-averaged dry deposition removal rates.

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• Oil Shale Fugitive Air Emissions and Plume Depletion

Objectives of this study are:

To develop model predictors for fugitive airborne particulate and gaseous emissions and plume depletion from oil shale and energy source industries in the mountainous regions of the western U.S.

To investigate dry deposition processes of fugitive emissions through the use of multiple tracers in field experiments to obtain area-averaged dry deposition removal rates.

RESULTS STATUS OF DUAL-TRACER FIELD EXPERIMENTS

G. A. Sehmel

Dry deposition experiments were conducted at night using the Hanford diffusion grid for measuring area-averaged removal rates during moderately stable to near-neutral conditions. The deposition area was 3.2 km in length across generally flat terrain with vegetation consisting of desert grasses and 1- to 2-m-high sagebrush. These dry deposition experiments for the DOE were conducted simultaneously with experiments sponsored by the EPA (Doran and Horst 1984). Different tracers were released in the DOE and EPA experiments. In the EPA experiments, the tracers were zinc sulfide (ZnS) particles and nondepositing sulfur hexafluoride (SF_6) tracer gas. In the DOE experiments reported here, two particulate tracers were released: uranine and lithium carbonate (Li_2CO_3).

The overall objective of this study was to investigate particle dry deposition for two nearly monodisperse tracer particle diameters from tracer particle/gas ratios. This article reports the status of data analysis for uranine and Li_2CO_3 tracer particles and the comparison of exposures for these tracers with exposures reported for ZnS and SF_6 tracers.

Experimental Procedures

The uranine and Li_2CO_3 tracer particles were released from water-alcohol solutions using two spinning disc generators. Originally the size characteristics of these tracers were evaluated with a quartz crystal microbalance (QCM) particle cascade impactor (Sehmel 1984). Tracer particle size characteristics were reevaluated in real time and with finer particle size discrimination using an optical particle counter. To determine the tracer size characteristics, tracers were generated in the inlet of a wind tunnel and were pulled slowly through the wind tunnel to allow evaporation. Particles were sampled as a function of time.

All tracer particles were polydispersed, with the average particle diameter increasing for the lithium, uranine, and ZnS particles, respectively. Mass-median diameters and geometric standard deviations were estimated from the size distributions for uranine and lithium particles. Estimates were made at the 50 mass percent of the distributions. However, it is emphasized that these are only estimates since the distributions were not log-normally distributed. Mass-average particle diameter was also calculated from the mass concentration (mg/m^3) and the number concentration (cm^{-3}). Size characteristics for all three tracers are summarized in Table 1. Although none of the tracer particles are monodispersed in size, there are

TABLE 1. Tracer Particle Size Characteristics for Assumed Log-Normal Mass Distributions

Tracer	Mass Average Diameter, μm	Mass Median Diameter, μm	Geometric Standard Deviation
Lithium-Traced	0.8 to 1.0	1.5 to 1.7	1.9 to 2.2
Uranine	1.4 to 2.6	4.4 to 5.1	1.7
Zinc Sulfide		4.8 to 8.0	1.8 to 2.4

significant differences in mass-median diameter for the three different particulate tracers.

The tracer release and sampling locations are described here since these affect the exposures as a function of azimuth. The uranine and Li_2CO_3 tracer particles were released at either 2.1- or 2.3-m heights during 6 experimental nights. The tracer plumes were somewhat different. As observed during the release, the maximum observed uranine tracer particle plume width was about 0.3 to 0.6 m, and could be seen for about 6 m. The maximum observed lithium tracer particle plume appeared wider, about 1 to 1.3 m, and could be seen for distances of only 3 m. Release heights were nearly the same as the 2-m height used for the ZnS and SF_6 releases. All four tracers were released with some lateral separation between sites along a line oriented from north to south. The Li_2CO_3 tracer particles were released from the most northern release site. The separation between the Li_2CO_3 and uranine release sites was 2 m. The SF_6 tracer gas was released 8 m south of the uranine release site. The separation between the SF_6 and ZnS release sites was less than 1 m.

To determine airborne tracer concentrations, tracer particulates were collected using open-faced membrane filters, 4.1 cm in diameter, exposed to the air. The SF_6 gas was collected using sampling bags. The particle tracer sampling density was much greater than it was for the SF_6 gas. Tracers were collected downwind at a height of 1.5 m along five sampling arcs of approximately 90° sectors each. The arcs were at 100, 200, 800, 1600, and 3200 m. Samples were collected along these arcs at only one height, 1.5 m. The spacing between samplers was 2° for the first three arcs, and 1° for the two most distant arcs.

In addition to surface sampling, limited vertical resolution of tracer concentrations was obtained with tower-mounted samplers from 0.2 to 24.8 m height at 106° and 122° azimuth along the 1600-m arc.

Chemical analyses for uranine and Li_2CO_3 tracer particles were done after ZnS analyses were completed. Since both of these tracers are water-soluble, they were removed from the filters by extraction with water: 7 ml of water were added to a vial containing a filter and the vial was vibrated for an hour. Most of the ZnS particles were removed by subsequent settling and decanting about 5 ml of the supernatant liquid into a centrifuge tube, centrifuging for 20 minutes, and using a syringe to withdraw about 4 ml of the clear liquid. Any particles remaining in suspension were removed by forcing the liquid in the syringe through a 5-μm glass-fiber prefilter and a 0.05-μm membrane filter. This liquid was analyzed fluorimetrically for uranine and by graphite-furnace atomic absorption for lithium.

Exposure Calculations

Airborne concentrations are converted to exposures, E, for both particulate and SF_6 tracers, i.e.,

$$E = \int C \, dt \, . \qquad (1)$$

The source-strength normalized exposure, E/Q (where Q = amount released), has units of s/m^3. For SF_6, the source-normalized exposure is calculated from the gas concentration in the bag:

$$E/Q = \overline{C} \, \Delta t/Q \, , \qquad (2)$$

where $\overline{C}$ is the measured concentration in a sampling bag and Δt is the sampling time for filling the bag. For particles the exposure is calculated from the mass of tracer, M, on the filter:

$$M = \int \varepsilon \, C \, F \, dt \, , \qquad (3)$$

where the isokinetic correction factor ε is assumed unity, and F is the sampling flow rate. For particles, the source-normalized exposure is

$$E/Q = M \, /(\varepsilon \, F \, Q) \, . \qquad (4)$$

Results

Selected source-normalized exposures for all four tracers are shown in Figures 1 and 2 for the June 12 experiment. These figures were selected to illustrate crosswind and vertical variations in exposures. For these exposure calculations, minimum concentrations outside the main plume were assumed to be representative of filter backgrounds for which filters

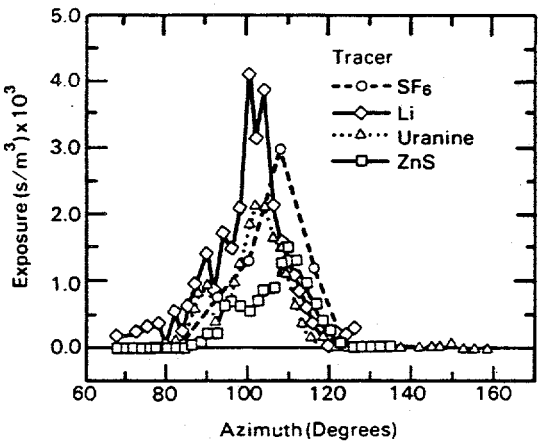

FIGURE 1. Crosswind Distributions of Tracers at 100 m on June 12.

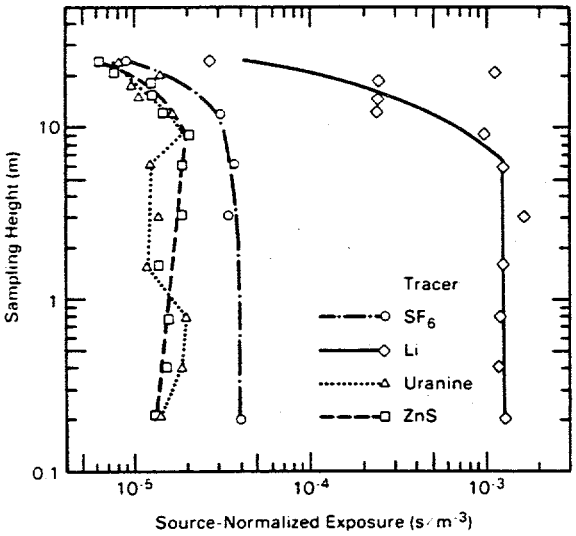

FIGURE 2. Vertical Distributions of Tracers at 1600 m at 106°Azimuth on June 12.

were uncontaminated with released tracer. Although backgrounds may be adjusted after further data analysis, general conclusions from these figures will remain the same.

Exposures at 1.5 m height are shown in Figure 1 as a function of azimuth for the 100-m arc, the first sampling arc. Maximum exposures for different tracers occur at different azimuths. These differences in azimuth reflect that the lithium and uranine tracers release sites were 10 and 8 m north of the SF_6 release site, respectively. Since tracer particles are removed by dry deposition and SF_6 tracer gas does not deposit, one expects that crosswind integrated concentrations of tracer particles and gas (the area under the curve) would be largest for SF_6 (integrations have not been done at this time). Indeed, crosswind integrated concentrations for uranine and ZnS particles are less than for SF_6 tracer gas. In contrast however, crosswind integrated concentrations for lithium tracer particles are greater than for the nondepositing SF_6 tracer gas.

As shown in Figure 2 for this June 12 experiment, lithium tracer particle exposures were also larger than for SF_6 tracer gas when measured as a function of height at the 106° azimuth of the 1600-m arc. Lithium tracer exposures are one to two orders of magnitude greater than expected by comparison with exposures for the other tracers. Nevertheless, exposures for both uranine and ZnS tracer particles are less than the exposure for SF_6 tracer gas. Exposures were nearly independent of height (within the limits of the data scatter) for heights between 0.2 m and about 9 m., i.e., decreased exposure adjacent to the soil surface was not observed. Within the upper portion of the measured plume, exposures tended to decrease with increasing heights from about 9 m to 24.8 m.

Conclusions

Experimental goals were accomplished since lithium and uranine tracer particles permitted the simultaneous evaluation of dry deposition for three different particle diameters. The three mass-median tracer particle diameters are 1.5 to 1.7, 4.4 to 5.1, and 4.8 to 8.8 μm. Results are being analyzed. Nevertheless, exposure results for both uranine and ZnS tracer particles support the concept that crosswind-integrated exposures for dry-depositing particles are less than exposures for nondepositing SF_6 tracer gas. Dry deposition velocities are to be calculated from the uranine tracer exposure data.

Crosswind-integrated exposures for lithium particles tended to be greater than for the nondepositing SF_6 tracer gas. Although

increased crosswind-integrated exposures for lithium particles may have resulted in increased exposures for lithium particles as a function of height at 1600 m (see Figure 2), the processes causing these increases need to be determined. The increase may have been caused by lithium released from the exhaust of gasoline-engine-driven vacuum pumps used for sampling particles along each arc. These pumps were located downwind of each arc.

Based upon data analysis to date, guidance in designing future experiments is suggested. Larger quantities of more monodispersed tracer particles and a more dense tracer sampling array are needed. Differences in exposures for the three tracer particles released may be a function of tracer particle diameter, or differences in local meteorology or tracer plume characteristics at each release site. During the experiments discussed, the uranine or ZnS particles would have subsided more rapidly by gravitational settling than the lithium particles, which were the smallest in diameter. Meteorological differences might be addressed by releasing all tracers as line sources, or by co-releasing all tracers into a chamber, mixing tracers in the chamber, and releasing all tracers through a common manifold or exit port.

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FEASIBILITY STUDY FOR DEVELOPMENT OF NEW ATMOSPHERIC TRACERS

J. Evans and K. Olsen

A number of species have proven useful as tracers of atmospheric air masses. Gaseous species that can be detected with great sensitivity include SF_6, perfluorocarbons, and deuteromethanes. New generations of experiments now being proposed, such as the Massive Aerometric Tracer Experiment (MATEX), require the tagging of multiple sources and detection at great distance (i.e., up to 1000 km). The currently available list of tracers is inadequate to fully satisfy this goal in a cost-effective manner. Furthermore, none of the particulate tracers currently available are fully satisfactory. Particulate tracers used in past work include nuclear weapons fallout, rare elements (e.g., lithium, iridium, indium, silver), ZnS, and fluorescent dyes. Development of new classes of tracers for both gaseous and particulate species is thus desirable. During the last year, a modest effort was initiated to identify potentially promising cases worthy of more detailed investigation. A number of important observations merged as detailed below.

1. Radioactive tracers should not be seriously considered. While one can demonstrate numerically that legally acceptable amounts of such tracers as ^{35}S can provide useful information, the political barriers appear to be insurmountable and analytical costs would be relatively high. Several more favorable cases were identified that require far smaller amounts of release due to the existence of methods for extremely sensitive detection. These include ^{10}Be, ^{26}Al, ^{36}Cl, ^{37}Ar, ^{53}Mn, ^{76}Ge, and ^{81}Kr.

2. One of the great advantages of the perfluorocarbons currently in use is that a single analytical method can detect two or three tracers at the same time. It would thus be desirable to introduce other new perfluorocarbon compounds into that analytical scheme. These compounds must be commercially available in large quantities at a manageable cost and at a moderately

high level of purity with respect to other tracer species. To explore this matter further, we initiated a dialog with representatives of the 3M Corporation, one of the largest suppliers of perfluorocarbon compounds. They advocated a group of SF_5 derivitized alkanes that are purported to have electron capture detection sensitivities approaching that of SF_6. Further laboratory investigation of the applicability of these compounds to atmospheric tracer applications is warranted.

3. The detection methodology for perfluorocarbons needs further development to enable to use of high-resolution chromatographic columns in place of the conventional packed columns. High-resolution chromotography provides greatly increased sensitivity and thus requires smaller releases. Positive effects of using more sensitive measurement techniques are reduction in global background buildup of these compounds and reduction of the costs for individual releases. Other compounds now in limited supply might also be able to be utilized.

4. Two deuterated compounds, perdeuteromethane and ^{13}C-labeled perdeuteromethane have proven very useful as long-range gaseous tracers. The utility of this class of compounds has been limited to those two by the analytical method used, mass spectrometry. The use of a detection system based on capillary column gas-chromatography microwave-induced helium plasma (GC-MIP) detection extends this concept to a potentially very large number of compounds with a variety of different properties. This concept looks very promising. We plan to investigate this further in the next year with a number of model deuterated compounds. This concept can be applied to both gaseous and particulate species.

5. The GC-MIP detector also has promise for detection of organometallic compounds released as tracers. A typical example would be beryllium acetylacetonate, a highly stable compound which could be used as a coating on fine particles. Environmental occurrence of this compound is expected to be vanishingly small. It has favorable properties for collection, extraction, and gas chromatographic analysis. Detection of beryllium by the MIP detector is extremely sensitive, rivaling that of the perfluorocarbons. This class of compounds is clearly worth further investigation.

• Particle Resuspension and Translocation

Objectives of this study are:

To develop model predictors for resuspension rates (and resulting airborne concentrations) of radionuclides and long-lived toxic chemical contaminants as a function of time, atmospheric and mechanical stresses, contaminant properties, and contaminated surface variables.

To investigate resuspension processes in field experiments using tracers and contaminated surfaces.

To investigate long time (weathering) effects on resuspension processes by evaluating airborne concentrations from aged plutonium and americium sources.

To investigate detailed resuspension processes by evaluating airborne concentrations in wind tunnel experiments.

TRANSURANIC RESUSPENSION

G. A. Sehmel

Characteristics of aged resuspension sources are more uncertain than those of new resuspension sources, which can be investigated using inert-particle controlled tracers. Even though airborne concentrations are low, one aged uniform-area source available for resuspension studies is the accumulated radionuclides in the soil from stratospheric and tropospheric fallout debris. Background research has been reported by Sehmel (1984), who summarized plutonium and americium resuspension research conducted by PNL from 1977 to 1983 for inclusion in the proceedings of the DOE Symposium on Environmental Research for Actinide Elements (Pinder 1985). Prior results obtained by Sehmel (1980) at Rocky Flats and Hanford between 1971 and 1977 were summarized previously.

Airborne concentrations from this source have been investigated at convenient sites on the Hanford site. This research evaluated important parameters of aged resuspension sources during field conditions:

- Is resuspension of fallout debris reflected by airborne plutonium concentrations that increase with greater wind speed?
- Are plutonium distributions a function of the aerodynamic particle diameters of airborne host-soil particles on which the plutonium was transported?

Sites Investigated

The resuspension of airborne plutonium was investigated at five sampling sites on the Hanford site, and airborne americium was investigated at two sites. Airborne plutonium and americium concentrations and activity densities were determined as functions of aerodynamic particle diameter, sampling height, wind speed increments, and wind direction increments. Samples were collected as a function of wind direction to partially control the effects on resuspension of upwind surface roughness and vegetative canopy. The wind direction selected was that which experienced the greatest frequency of high wind speeds: southwest. Sampling heights ranged from 0.3 to 124 m above ground.

Conclusions

Wind resuspension of surface contamination continues for many years. Continued resuspension was shown from investigations of airborne plutonium and americium concentration ($\mu Ci/cm^3$) and activity densities on airborne solids ($\mu Ci/g$) resuspended from aged sources. Results indicate airborne concentrations and activity densities for aged resuspension sources are functions of host-particle diameter, sampling height, wind speed, and wind direction (direction of highest frequency of high wind speeds). This data base is important for directing predictor development for long-term environmental assessment effects.

In general, predictors need to consider the following dependencies:

- Compared to activity densities (μCi/g) for bulk soil samples, radionuclides are enriched on airborne respirable-particle sizes.

- Most resuspension sources are nonuniform in surface contamination per unit area. For nonuniform resuspension sources, airborne concentrations are functions of height; maximum airborne concentrations can be near the surface or at greater heights.

- The apparent wind speed dependency of airborne concentrations can be influenced by upwind terrain variations. For sites in relatively flat terrain, plutonium concentrations tend to increase according to a power function of wind speed. When a power law dependency is assumed, U^n, the exponent n ranges from 0.8 to 7.8. For a mountaintop site, airborne concentrations are more complex functions of wind speed.

- Americium/plutonium activity ratios may not be unity and can be a function of wind speed.

An activity density relationship was developed from activity densities on airborne solids and surface soils at the Bikini atoll, the Hanford site, and the Rocky Flats site, for improved predictions of airborne concentrations from wind resuspension. The relationship is useful for predicting airborne concentrations above contaminated areas, but has less utility for predicting airborne concentrations downwind. An important predictive improvement from the correlation is that resuspension-factor ranges can be predicted now more accurately as a function of the resuspension-source activity densities. These predicted resuspension factors could be used in long-term assessments for aged resuspension sources.

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WIND RESUSPENSION OF SOILS COVERED WITH ROCK CANOPIES

G. A. Sehmel and W. H. Hodgson

Although materials in the environment are being transported by suspension processes, generalized predictors have not been developed for wind-caused suspension of surface-deposited materials. Detailed information is needed on the resuspension processes. It is believed that resuspension processes are a function of properties of both deposited materials and host-soil particles upon which these materials are deposited. Although real-time concentrations of suspended matetials are needed for evaluating suspension processes, this is currently not economically achievable in real time as a function of particle diameter. Hence, the physics of real-time suspension processes were investigated for soil particles that might be host particles for suspension of materials of respiration concern.

Soil suspension processes were investigated in a wind tunnel by measuring airborne concentrations of suspended soil in real time with an optical particle counter. The cross section of the wind tunnel was 2 by 2 ft, and the test section length used was 12 ft; i.e., 12 ft of the wind tunnel floor were covered with soil, which was the source of airborne particles.

Airborne particle concentrations were reduced before the air passed over the test section. To ensure that the soil was the source of measured airborne concentrations, laboratory air was drawn through a 6 by 6 ft bank of high-efficiency filters before it reached the converging section of the wind tunnel. Background airborne concentrations were measured in the converging section and subsequently

subtracted from airborne concentrations measured above the test section.

Experimental Procedures

Suspension from the soil surface was investigated as a function of different rock-canopy densities and depths placed on the underlying soil surface. The rock was river rock, from a 1/2 to 1 in. screen size. The soil was collected adjacent to a tracer resuspension site near Horn Rapids Dam, oven dried, and sized to less than 0.046 in. (1.168 mm).

The following sequence of increasingly complex of surface covers was investigated:

Smooth soil surface. The initial surface was soil uniformly spread across the 2-ft width of the wind tunnel floor. This soil-covered test section was 12 ft in length. Airborne concentrations were usually measured near the downwind edge of the test section, at 11.6 ft.

One layer of rock. In order to increase turbulence and cause suspension, single cross-wind rows of 1/2- to 1-in. screen-size rocks were placed on top of the soil. Rocks were placed at 2-in. spacing across the width of the wind tunnel. Rows were at 1-, 2-, 3-, 7-, 8-, and 9-ft distances.

Next, the rock coverage was increased with five rows of rock placed on top of the soil downwind of each single row. Rocks were placed in a 2-in. equilateral triangular array. Hence, the soil remained uncovered between the 4- and 7-ft distances.

Finally, the entire soil surface was covered with rock in a 2-in. equilateral triangular array.

Because rocks were in a size range, there were nonuniform gaps between rocks when the rocks were placed in a 2-in. equilateral-triangular array. These gaps between rocks were filled in with additional rocks.

Two layers of rock. Since soil continued to be suspended when the soil was covered with one layer of rock, a second layer of rock was added to investigate effects of depth of rock cover in reducing suspension. The second layer of rock was placed in a close-packed array on top of the first rock layer.

Three layers of rock. Since soil continued to be suspended when the soil was covered with two layers of rock, a third layer of rock was added to increase the depth of rock cover. The third layer of rock was placed in a close-packed array on top of the second rock layer.

Measurements

Airborne particle concentrations and air velocity profiles were measured as a function of wind speed, time, and height above the test section in the wind tunnel. In addition, friction velocity and aerodynamic surface roughness were evaluated from velocity profiles measured with a pitot tube while using a sloping manometer.

Airborne particle concentrations were measured in real time with one optical particle counter. Ideally in measuring concentrations as a function of height, two counters would have been preferable. The inlet probe location of one counter would be held constant in order to normalize concentrations measured with a second roving probe. Since only one counter was available for use, a required assumption in cross-comparing data is that surface properties did not change during a series of a few successive experiments. Particle are sized between 0.5- and 15-μm diameter into 49 size intervals. There are 32 size intervals per decade of particle diameter (logarithmic). Reported here are the number concentrations (number/cm^3) for selected size intervals.

Results

This is a data-intensive experiment; there are over 21,903 datum points in the 447 experimental runs conducted. Some data were hand-plotted during the conduct of the experiments in order to plan succeeding experiments. Also, some data were plotted using computer programs. However, the bulk of the data has not been examined. These data are on computer files.

Selected results are discussed as a function of friction velocity and height for suspension from a smooth-aged soil surface. Airborne concentrations at 1-in. height are shown in Figure 1 as a function of aerodynamic friction velocity (from 5 to 20 mph maximum wind speed) and particle diameter.

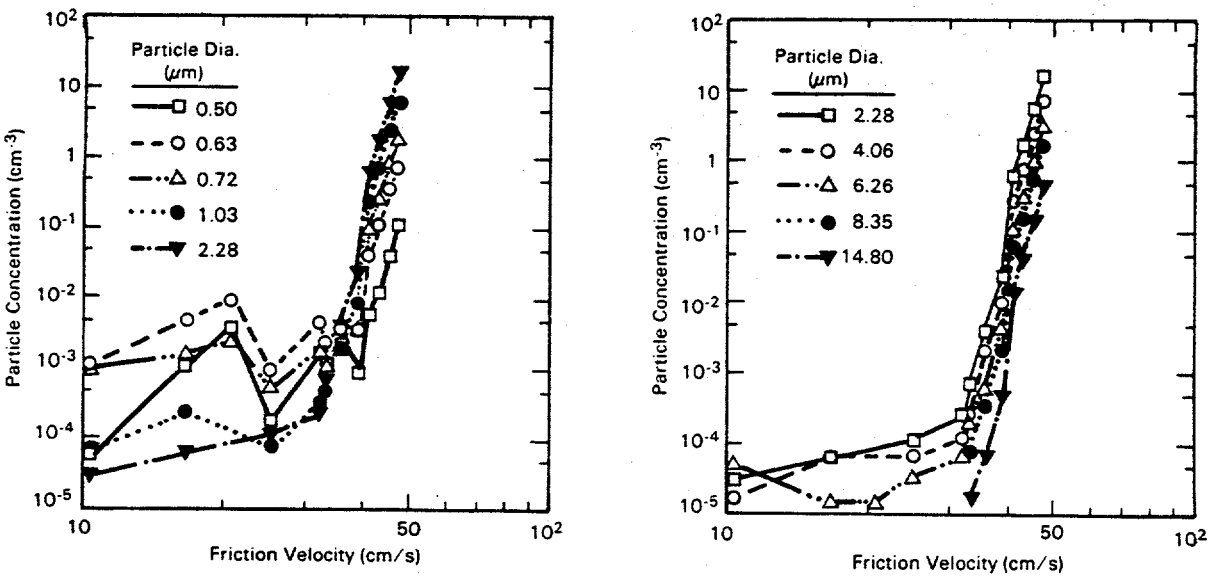

FIGURE 1. Airborne Particle Concentrations at 2.5 cm Above a Smooth-Aged Soil Surface as a Function of Particle Diameter and Friction Velocity.

The maximum airborne concentrations were for the 2.28-μm diameter particles. The left subfigure is for particle diameters $\leq$2.2 μm, and the right subfigure is for particle diameters $\geq$2.2 μm. It is significant that all particle diameters suspend, from at least 0.5 to 15 μm diameter. Furthermore, airborne concentrations increase rapidly for friction velocities greater than about 30 cm/s. When a power law dependency is assumed for the rate of increase, u_*^n, the exponent n is about 16.

The suspension processes causing this transition near a friction velocity of 30 cm/s also cause a change in the aerodynamic surface roughness; the roughness height increases from about 0.002 cm to 0.006 cm. Possibly, the soil surface is lifted by air drag, expands and tends to become fluidized, with particles being released during the fluidization.

Airborne concentrations for a constant friction velocity of 38.7 cm/s are shown in Figure 2 as a function of height. Concentrations decrease rapidly as a function of height. The rate of decrease is approximately constant for all particle diameters. When a power law dependency is assumed, z^n, the exponent n is -3.2.

The following tentative generalizations are made from the other airborne concentration data that have been examined:

- Resuspension is rapid from a freshly deposited dry soil.

- Resuspension during a constant wind speed decreases with time until the surface becomes weathered. At present this weathering time cannot be predicted, but the effects of surface weathering are apparent from the decreased concentration data.

- Below the friction velocity transition range for the soil surface, airborne concentrations sometimes tend to segregate into two separate data sets that reflect the resuspendability of the soil surface. The data set with lower concentrations may indicate the most stable condition of the soil surface. Nevertheless, instabilities can occur. The data set with greater concentrations may reflect instability effects.

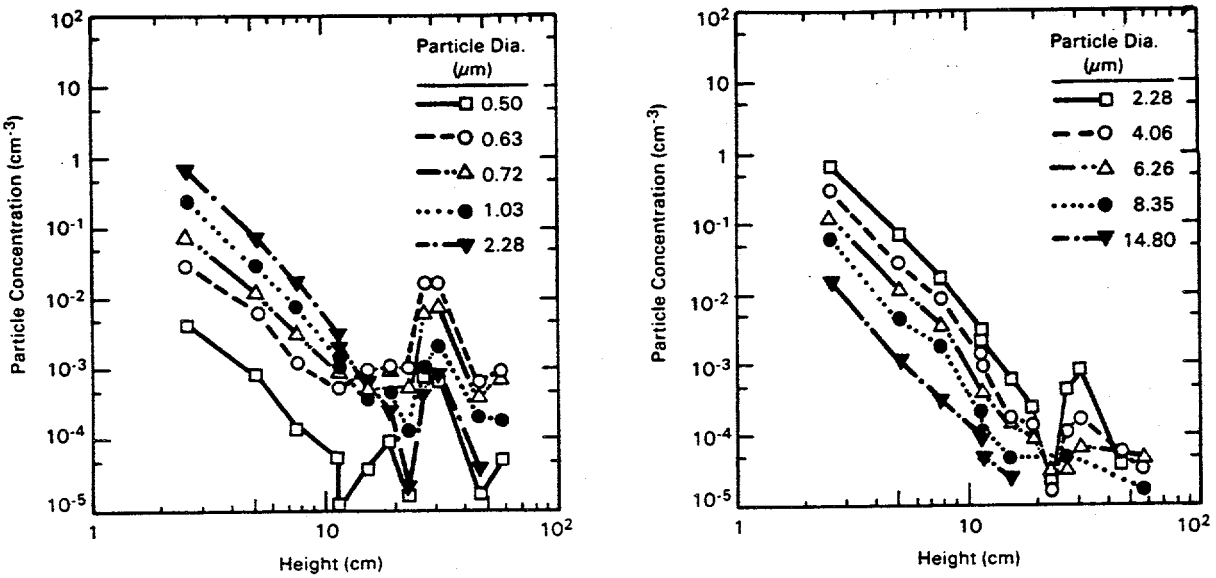

FIGURE 2. Airborne Particle Concentrations Above a Smooth-Aged Soil Surface as a Function of Particle Diameter and Height for a Constant Friction Velocity of 38.7 cm/s.

Conclusions

All particle diameters investigated were resuspended by wind stresses. Results indicate that airborne concentrations can increase rapidly above a transition friction velocity range near 30 cm/s for a soil surface. Although suspension occurs, concentrations can decrease very rapidly as a function of height. This decrease infers that during investigations of wind suspension of surface contamination, airborne concentrations would probably have decreased orders of magnitude at heights usually used, i.e., near respiration height for adults. Because of this rapid concentration decrease with height, potential exposures to children and animals in a contaminated area might be underestimated.

A large data set remains to be analyzed. Nevertheless, results show that resuspension occurs even though the soil is covered with three layers of rock. Even though air is slowly moving between the rocks, air motion is sufficient to suspend particles from the underlying soil.

• Theoretical Studies and Applications

Objectives of this study are:

To develop mathematical models that realistically characterize and describe the fate of energy related-air contaminants.

To translate theory and data into forms most useful for practical application in evaluating the consequences of air contaminant releases.

THEORETICAL STUDIES AND APPLICATIONS

W. G. N. Slinn

The Theoretical Studies and Applications project was concluded, after 10 years of study, in FY-1984. The purposes of the project were 1) to develop theoretical models to characterize and to describe the fate of energy-related pollutants and 2) to translate the theory (and data from laboratory and field studies) into forms most useful for practical applications--evaluating consequences of air pollution releases.

During this final year, a chapter on Precipitation Scavenging, by W. G. N. Slinn, was published in Atmospheric Science and Power Production (Randerson 1984); this volume is the sequel to Meteorology and Atomic Energy (Slade 1968). This chapter illustrates the realization of the two goals of the project, i.e., theoretical developments and practical applications.

This article summarizes other accomplishments of this project and indicates new initiatives that have been derived, in part, from this project.

Accomplishments

The publications listed in Table 1 have been funded wholly or in part by this project. All of these were written by W. G. N. Slinn, with coauthors as noted. These publications document knowledge gained in this study.

New Initiatives

During FY-1984, some support from this project has been used to fund efforts on major new research initiatives for DOE. Brief descriptions of four of these new initiatives are given in the following paragraphs. All of these initiatives are in the fields of precipitation scavenging, dry deposition, and resuspension. Omitted from below is a description of a major new project in precipitation scavenging, entitled PRECP: PRocessing of Emissions by Clouds and Precipitation. The PRECP project is described in the next article in the annual report.

During FY-1984, W. G. N. Slinn wrote first drafts of two major proposals in dry deposition. The titles of the initiatives are now ASDEP (Atmospheric-Surface Dry Exchange Processes) and TDEP (Tracer-Simulated Dry Deposition of Environmental Pollutants). Both proposals have been submitted to the DOE-Office of Health and Environmental Research (OHER) and funding is anticipated to start in FY-1986. The portion of the original ASDEP proposal that has been recommended for funding by Task Force D of the Interagency Task Force on Acid Precipitation will be led by Argonne National Laboratory; this portion proposes to measure area-averaged dry deposition by means of eddy-flux measurements from aircraft. The portion of the original ASDEP proposal that is now TDEP has received favorable review by the Office of Management and Budget; this portion proposes to use tracer and other methods to determine dry deposition of acidic and other pollutants. A scientific peer review of research plans for both approaches is planned for the near future.

Preliminary work on a third new initiative to DOE-OHER has also been conducted. The proposed research is to use radioactive tracers at Department of Energy sites to study exchange processes between the atmosphere and terrestrial surfaces, especially the resuspension of particles. The program was outlined by W. G. N. Slinn at a resuspension workshop hosted by the Lawrence Livermore National Laboratory (LLNL) during the summer

TABLE 1. Publications from the Theoretical Applications Task, 1974 through 1984

"The redistribution of a gas plume caused by reversible washout," *Atmos. Environ.*, 8:233, 1974.

"Rate limiting aspects of in-cloud scavenging," *J. Atmos, Sci.*, 31:1172, 1974.

"Atmospheric aerosols in surface-level air," *Atmos. Environ.*, 9:763, 1975.

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"Precipitation scavenging of aerosol particles," *Geophys Res. Letters*, 3:21, 1976.

"Buoyant plumes: closure problems and dissipative processes," *Atmos. Environ.*, 10:665, 1976.

"Formulation and a solution of the diffusion-deposition-resuspension problem," *Atmos. Environ.*, 10:763, 1976.

"Dry deposition and resuspension of aerosol particles—a new look at some old problems," *Air-Surface Exchange of Particulate and Gaseous Pollutants.* R. J. Engelmann and G. A. Sehmel (coords.), ERDA CONF-740921, 1976. Available from National Technical Information Service, Springfield, Virginia.

"Theory of diffusive deposition of particles in a sphere and in a cylinder at small Fourier numbers," *Atmos. Environ.*, 10:789, 1976.

"Some approximations for the wet and dry removal of particles and gases from the atmosphere," *J. Water, Air, and Soil Pollution*, 7:513, 1977.

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"Some comments on parameterization for resuspension and for wet and dry deposition of particles and gases for use in radiation-dose calculations," *Nuclear Safety*, 19:205, 1978.

"Some aspects of the transfer of atmospheric trace constituents past the air-sea interface—a review," with L. Hasse, B. B. Hicks, A. W. Hogan, D. Lala, P. S. Liss, K. O. Munnich, G. A. Sehmel, and O. Vittori, *Atmos. Environ.*, 12:2055, 1978.

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"Predictions for particle deposition on natural waters," with S. A. Slinn, *Atmos. Environ.*, 14:1013, 1980.

"Relationships between removal processes and residence times for atmospheric pollutants," A.I.Ch.E. Symp. Series 76, 185, 1980.

"Modeling Air Pollution Fluxes to Natural Waters," with S. A. Slinn, Chapter 2 of *Atmospheric Input of Pollutants to Natural Waters*, S. J. Eisenreich (ed.), Ann Arbor Science Publishers, Ann Arbor, Michigan, 1981.

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"Some Influences of the Atmospheric Water Cycles on the Removal of Atmospheric Trace Constituents," invited chapter in *Atmospheric Chemistry*, E. D. Goldberg (ed.), Springer-Verlag, Berlin, 1982.

"A potpourri of deposition and resuspension questions," in *Precipitation Scavenging, Dry Deposition, and Resuspension*, H. R. Pruppacher, R. G. Semonin, and W. G. N. Slinn (coords.), Vol. 2, Elsevier, New York, 1983.

"Air-to-Sea Transfer of Particles," Chapter 6 of *Air-Sea Exchange of Gases and Particles*, P. S. Liss and W. G. N. Slinn (eds.), Reidel, Boston, 1983.

"Sources and surface-area distributions of atmospheric particles," *Atmos. Environ.*, 17:2363, 1983.

"Estimates for pollution profiles above finite-area sources," with T. W. Horst, *Atmos. Environ.*, 18:1339, 1984.

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of 1984. Participating laboratories are proposed to be LLNL, Los Alamos National Laboratory, Oak Ridge National Laboratory, Savannah River Laboratory, and PNL. A first draft of the proposed research has been submitted to DOE-OHER.

The fourth applications topic, to which this project contributed during FY-1984, dealt with the "nuclear-winter issue." W. G. N. Slinn was invited to attend a workshop on the influence of precipitation scavenging on predictions of nuclear winter. The workshop was sponsored by the International Council of Scientific Unions, Scientific Committee on Problems of the Environment (ICSU-SCOPE) and was held in conjunction with the Ninth International Cloud Physics Conference, Tallinn, Estonia, USSR. Publication of the results of the investigation of this application of precipitation scavenging by W. G. N. Slinn is expected in the near future. A summary statement is that it appears that the duration of any "nuclear winter" has been overestimated because of inadequate modeling of precipitation scavenging; however, the severity of consequences of nuclear war may have been underestimated.

Acknowledgments

Productivity during the ten years of this project would have been substantially less had it not been for the application of competent administrative skills by R. W. Beadle, D. S. Ballantine, and C. E. Elderkin.

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Slade, D. H., ed. 1968. Meteorology and Atomic Energy. TID-24190, U.S. Atomic Energy Commission, Division of Technical Information, Oak Ridge, Tennessee.

• Processing of Emission by Clouds and Precipitation

The objective of this study is:

To define and reduce current uncertainties in wet processing rates, ratios, and efficiencies so that resulting uncertainties in "acid-rain" source/receptor models are known and acceptable.

PRECP: OVERVIEW OF NEAR-TERM PROGRAM PLANS

W. G. N. Slinn

PRECP (PRocessing of Emissions by Clouds and Precipitation) is one of the projects under Task Group C (Atmospheric Processes) of the National Acid Precipitation Assessment Program (NAPAP). The PRECP program is being conducted by staff at three member laboratories of the National Laboratory Consortium (NLC): Argonne National Laboratory (ANL), Brookhaven National Laboratory (BNL), and the Pacific Northwest Laboratory (PNL), and by staff from university and private-industry subcontractors. The purpose of this article is to provide an overview of objectives and near-term plans for the PRECP program.

Objectives and Applications

The objectives of the PRECP program is to improve understanding of the chemical and physical processing of emissions by clouds and precipitation. This understanding will be sought through analysis of appropriate data, through model development and testing, and through laboratory and field studies. When translated into mathematical models, this understanding will be used for the definition of relationships between pollutant releases and subsequent deposition of acids.

To accomplish this "applications-objective," communication channels have been opened to transfer the understanding developed in PRECP to user communities. Four important examples of these communication links are:

- A major acidic-deposition assessment tool used by the DOE is a Lagrangian numerical model under continuous development at ANL; PRECP results will be incorporated into this ANL Lagrangian model.

- Related field studies are being conducted by BNL for both EPA and the Electric Power Research Institute; these studies will benefit from interactions with PRECP (and vice versa).

- Under EPA sponsorship, the Pacific Northwest Laboratory is responsible for supplying the "Precipitation Scavenging Module" for the Regional Acid Deposition Model (RADM) being developed at the National Center for Atmospheric Research (NCAR), and through individual staff member involvement in both projects, PNL will apply PRECP results directly to this EPA "Scavenging-Module" development.

- To ensure that PRECP data and results are communicated promptly to potential users, the Scientific Coordinator of PRECP (P. Michael, BNL) maintains frequent contacts with the RADM staff at NCAR, with Task Group C (the Coordinator is the NLC's representative on Task Group C), and with the NAPAP acid deposition assessment staff.

Activity Categories

Activities supporting the accomplishment of PRECP goals are:

- program guidance
- field studies
- analysis of previous data
- instrumentation implementation and quality assurance
- laboratory studies
- theoretical and interpretative modeling.

Brief descriptions of proposed near-term activities in these categories are given below.

Program Guidance

Summaries of current knowledge and needed research are being written to guide PRECP. Three summaries, expected to be completed in the near future, deal with:

1. cloud chemistry,

2. storm processing of pollutants, and

3. applications to regional-scale models.

Lead authors for these summaries are L. Newman, W. G. N. Slinn, and P. Michael, respectively.

Field Studies

The overall objective of the field studies component of PRECP is to contribute to understanding the processing of pollutants by clouds and precipitation through observations. Specific objectives include testing specific hypotheses and questions, and providing a data base for testing applicable numerical models.

A series of preliminary field measurements is planned starting in the spring of 1985 and extending through the winter of 1986. These measurements will be conducted during three or four separate field expeditions, each of approximately one-month duration, during the first year. This schedule will allow development and testing of flight and sampling protocols under a variety of meteorological conditions characteristic of these seasons and will also provide documentary information regarding the seasonal and meteorological dependence of the concentrations of acid precursors and oxidants.

The first in this series of measurements will start in April 1985. In this study, emphasis will be placed on developing techniques to study stratus and orographic systems and on sampling frontal storms. Close coordination is planned with the concurrent EPA program concerning urban effects on precipitation composition. The intensive network of precipitation samplers deployed in the EPA program will allow assessment and comparison of precipitation samples collected on the ground and by aircraft and will also allow study of the chemical and meteorological processes causing the "signatures" observed in precipitation composition downwind of Philadelphia. Study of the latter may reveal processes important in determining the relationship between emissions and deposition on a larger scale.

Field measurements being planned for both the spring and summer of 1985 will concentrate on developing techniques to study convective clouds and storms, and to document summertime concentrations of oxidants, acids, and acid precursors. Of particular interest is development of the capability to measure the chemical composition of the outflow air of cumulonimbus clouds, (e.g., in conjunction with the National Oceanic and Atmospheric Administration (NOAA) PRE-STORM study). By comparison of the chemical composition of the inflow and outflow air in cumulonimbus clouds and mesoscale convective systems, assessment can be made of the extent to which these clouds have incorporated materials present in the pre-cloud air and, thus, whether these systems are linear or nonlinear. Consideration is also being given to collaboration with NOAA on a proposed experiment in which SO_2 would be released into a cloud from a mountain-top location.

During the winter of 1986, in addition to documenting the concentrations of pertinent chemical species under winter conditions, efforts will be expended on developing techniques for the airborne collection of supercooled cloudwater and snow, and on developing and testing experimental protocols for processes expected to be important in winter storms, e.g., below-cloud scavenging of HNO_3. If feasible, these experiments will be done in conjunction with the GALE project. If such collaboration proves possible, a larger scale study, designed to take advantage of the detailed meteorological measurements from GALE, will be executed.

Analyses of Previous Data

Data on the physical and chemical precipitation climatology of North America are being organized to aid PRECP field studies. Near-term goals include:

1. Define expected chemical conditions for PRE-STORM (midwestern U.S.) by January 1985 and GALE (mid-Atlantic U.S.) by July 1985.

2. From available surveys and National Weather Service/National Climatic Center data, define a first-cut storm/precipitation categorization scheme for the northeastern U.S. by October 1985.

3. Review previous field study campaign data (e.g., APEX, METROMEX, OSCAR, Philadelphia), with regard to PRECP field study plans and goals, and report as results become available.

4. Characterize precipitation chemistry in the northeastern U.S. and southeastern Canada according to air mass and storm type (complementary to item 2).

Defining the relationships between precursor emissions and wet deposition is an overall goal of PRECP, and studying existing data for this purpose can provide direct evidence on a macroscale, which complements the process-oriented studies in other areas. Relationships can be defined in two ways:

- through use of temporal variations in emission and deposition. Long-term records are generally needed for this purpose, to deal with stochastic variability and to provide a sufficient range of variability in precursor emissions.

- Through short-term spatial variability in deposition as related to trajectories and meteorological conditions. Contemporary (event) network data and recent field-campaign data are used for these studies.

In both cases, statistical reliability may be improved by drawing on corresponding ancillary environmental data, such as air quality, atmospheric turbidity or extinction, or surface water quality (long-term trends).

Instrumentation Implementation and Quality Assurance Activities

The objectives and strategy of this activity are:

- to implement instrumentation technologies for unambiguous sampling of gases, aerosols, clouds, and rainwater from ground and airborne platforms, and for measurement of critical chemical species and meteorological parameters above background with reasonable time resolution. Existing technologies (or modest extensions therefrom) will be used, with emphasis on rigorous documentation of applicability under conditions expected in the field studies.

- to develop quality assurance (QA) procedures for PRECP activities such that the chemical and meteorological data sets acquired through ground and airborne measurements have established and quantified error limits, and that error contributions from sampling and analysis are separable from fluctuations in source strengths and the natural variability of deposition processes.

Laboratory Studies

Since in-cloud reactions for acid generation are potential sources for chemical nonlinearity, their reaction kinetics have to be fully characterized. The overall reaction rates of these gas-liquid reactions are affected by one or more of the following quantities: reagent solubility, reaction kinetics and stoichiometry, mass transfer limitations, phase transition of the cloudwater, and catalysis or inhibition of trace material present in cloud and rainwater. The accurate evaluation of the contribution of a particular reaction to acid generation, therefore, depends on our knowledge on these quantities.

For the near-term study, effort will be focused on the chemical and physical processes that are likely to affect all of the gas-liquid reactions in a general way. These include the rate of incorporation of gaseous reagents into the liquid phase, the effects of phase transition of cloudwater from liquid to ice on the solutes and their reactions, and the effects of trace organic and inorganic material in rain and cloudwater on some of the important S(IV) oxidation reactions. Consequently, the objectives of the laboratory studies for the near term are:

- to measure rates and extents of dissolution/adsorption of gaseous reactants and oxidants into/on aqueous droplets and ice particles,

- to measure rates of acid production in the aqueous phase (liquid or solid), and

- to determine the effects of trace material present in rain and cloudwater on certain important in-cloud oxidation reactions.

Modeling Studies

Theoretical descriptions and model simulations of the physical and chemical processes leading to the deposition of acidic substances are required in order to test hypotheses, design and analyze experiments, understand the relationships among many variables in a complicated system, and ultimately to contribute to the description of the effects of nonlinearities upon the change of deposition as a function of emission changes.

Several subobjectives have been identified:

- Determine consequences of laboratory-derived kinetic data under representative and actual cloud conditions.

- Seek interpretations of experimental data.

- Define detection limits, precision, and accuracy required in experiments to address specific hypotheses.

- Determine pollutant concentrations, profiles, etc. that can serve as readily recognizable signatures of physical and chemical processes.

- Predict concentrations of substances not readily measured, for understanding the subsequent in-cloud chemistry and for understanding site-to-site, storm-to-storm, and season-to-season variability in measured concentrations.

- Provide theoretically consistent models of acid production, starting with cloud inflow conditions and ending with precipitation on the ground.

- Determine the extent of reprocessing of pollutants from one storm to another.

- Determine the climatological significance of different storm types and episodic conditions.

These objectives will be accomplished through the use of different types of models denoted in the program as "diagnostic", "storm scale", and "perspective". The term "diagnostic" refers to models that emphasize detailed descriptions of particular processes, "storm scale" refers to models that follow pollutants from cloud inflow air to precipitation, and "perspective" refers to models that determine regional-scale implications of single-cloud or storm findings.

The storm-scale models will be based upon an advection/diffusion equation solver, driven by wind and moisture fields obtained from observations or from meteorological models, and containing parameterized descriptions of cloud microphysics and chemistry as derived from the diagnostic models.

Near-term activities are to

- seek the participation of modeling groups from outside the National Laboratories,

- continue simulations of cumulus clouds,

- develop storm-scale models by interfacing an advection/diffusion equation solver (PLUVIUS or STEM) with meteorological data and with cloud microphysics and chemistry descriptions,

- analyze the proposed plume-cloud interaction experiment, and

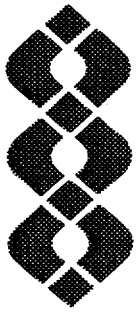
- plan for the calculations required to assess the regional-scale implications of single-cloud findings.

Support Activities

Explicit provision has been made to provide for scientific coordination, subcontracting, and related support activities. Important goals are to ensure that there is close collaboration among the participants and with researchers in other programs, to coordinate the involvement of university and other research groups in PRECP, to provide for an efficient data exchange among the program participants, and to archive the data for future use.

Acknowledgments

This summary of PRECP near-term plans has relied heavily on contributions from many participants in the PRECP program, both at the National Laboratories and elsewhere. Explicit mention should be made of the contributions by laboratory-associated personnel: D. Slade, P. Michael, L. Newman, R. Hadlock, R. Tanner, Y-N. Lee, L. Kleinman, T. Dana, W. Davis, A. Leslie, and C. Lindsey, and by W. Brost, G. Carmichael, W. Cotton, H. Harrison, D. Hegg, M. Hjelmfelt, W. Johnson, D. Lamb, H. Orville, J. Pflaum, D. Stedman, W. Stockwell, P. Summers, G. Vali, and M. Wolf.



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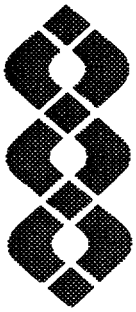

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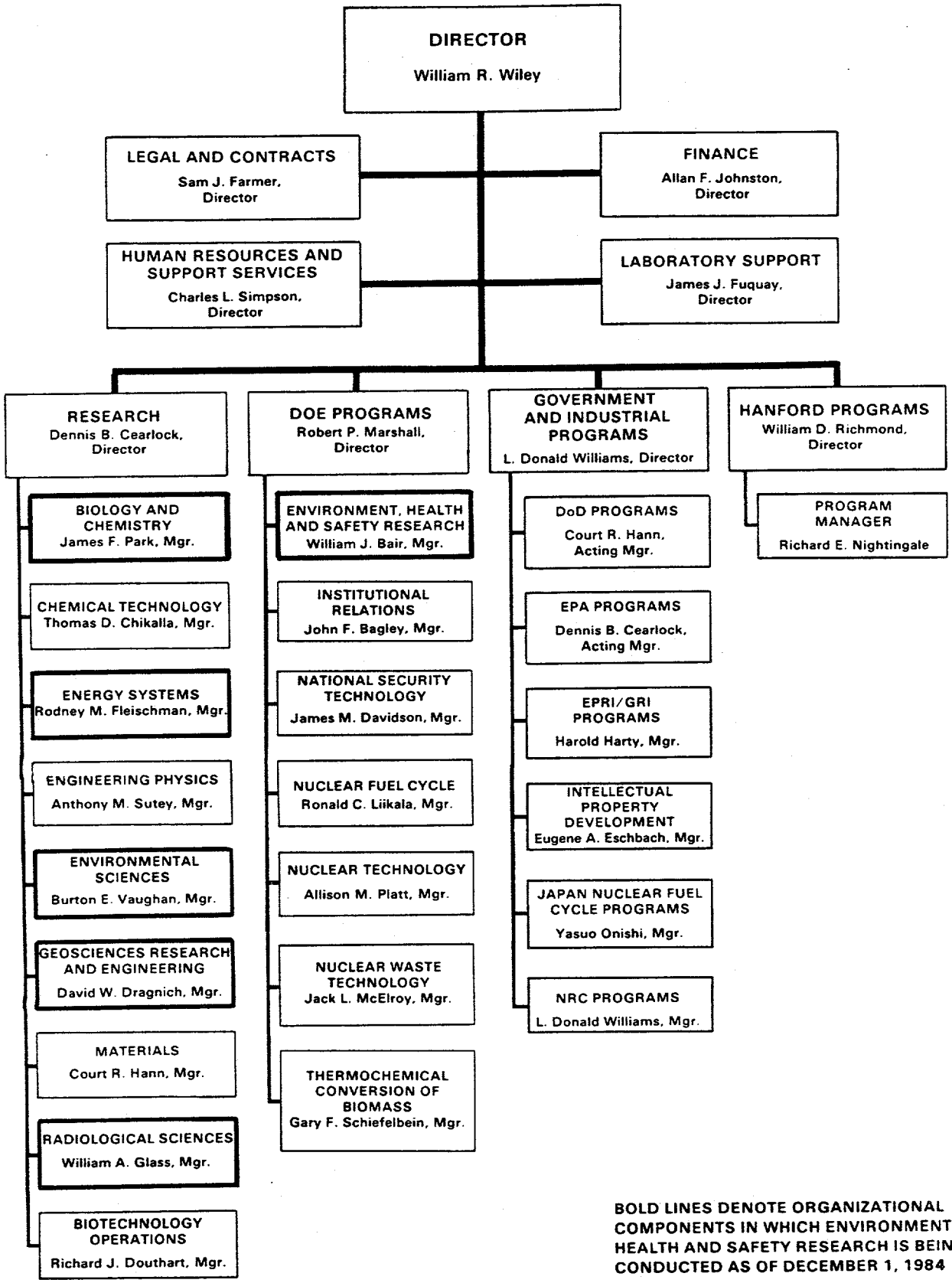

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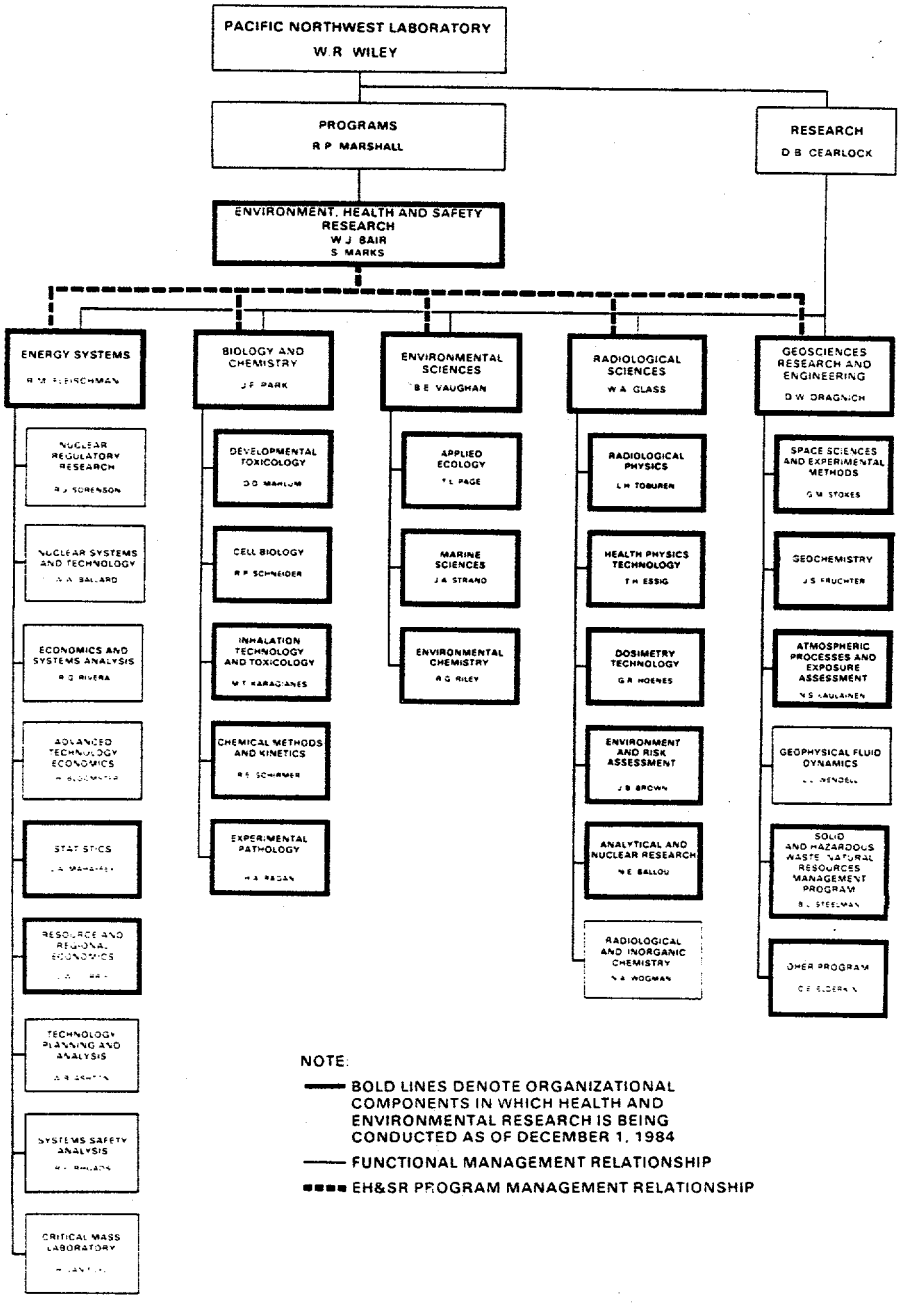

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